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THE UNDERWATER ENVIRONMENT OF DOUBTFUL SOUND :

RESULTS FROM AN INSTRUMENT ARRAY MOORED FROM NOVEMBER 1987 TO JUNE 1989

K.R. Grange[1], R.J. Singleton[1], W.M. Goldberg[2], P.J. Hill[1]

ABSTRACT

An environmental monitoring instrument array (EMA) was moored at Tricky Cove, Doubtful Sound, from November 1987 to June 1989. Quantum sensors were deployed above the surface and at 9 m depth, while temperature and conductivity cells were deployed at 4 m, 7 m, and 15 m. Outputs from each were logged hourly by a LICOR Datalogger. All sensors were cleaned and batteries replaced monthly when the datalogger memory was transferred to disk. EMA was designed to collect environmental data of possible significance to growth-band formation in colonies of the black coral *Antipathes fiordensis* growing at the site. This report presents the daily and monthly means from all sensors, and describes the variability in light, temperature, and salinity underwater for the first time in a New Zealand fiord. Air temperature and rainfall at Deep Cove over the same period are also presented, and brief comparisons made with long-term mean sea-surface temperatures off Milford Sound. Seasonal changes in underwater light and temperature can be identified, and heavy rain causes rapid fluctuations in salinity below the surface layer. Light penetration underwater is high, particularly in winter, but absolute values are low.

Keywords : Temperature, salinity, light levels, irradiance, fiords, New Zealand, monitoring, marine environment, meteorology

INTRODUCTION

The New Zealand fiords are well known for the prodigious rainfall that occurs all year round. Mean annual rainfall at Milford Sound is 6267 mm (Pickrill 1987), and at Deep Cove is 5290 mm (Stanton & Pickard 1981). The small catchments surrounding the fiords respond rapidly to rainfall, as do river discharges, with daily peak flows coincident with daily peak rainfall. The fiords have typical fiord-estuary patterns of temperature and salinity; the high runoff of fresh water leads to the formation of an upper layer of low salinity moving seaward over a marked halocline at 5–10 m depth (Pickrill 1987), although direct observations made underwater show the halocline at 4 m for most of the time. Recent work (Grange & Singleton 1988; Grange 1990) has shown that the unusual climate probably has profound effects on the biological processes that occur in these fiords.

The most comprehensive physical oceanographic data are those of sea-surface temperatures, taken at Anita Bay near the entrance to Milford Sound, as part of the NZOI coastal climate survey (Stanton 1986). The monthly means for the period 1979–1983 showed that the annual sea-surface temperature range is from 11.5 °C in September to 14.9 °C in March (Stanton 1986, Fig. 5). Considerable short-term variation was reported, however, with an extreme range for the same period being 9.3–15.7 °C. From 1934–1980, the mean air-temperature range at Milford Sound was approximately 5.5–14.5 °C (Stanton 1986).

Results of salinity samples throughout the fiords have been reported by various workers (Garner 1964; Batham 1965; Jillett & Mitchell 1973; Stanton 1978, 1984, 1986; Stanton & Pickard 1980, 1981; Pickrill 1987), all of whom have identified a low-salinity surface

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layer moving seaward over water of near-coastal salinity. Surface salinities have been reported as low as 5.9 practical salinity units (equivalent to parts per thousand) (*see* discussion in UNESCO 1985) in Milford Sound, 20–30 psu throughout the Doubtful Sound complex (Stanton 1984), and 21–22 psu in Doubtful Sound during summer 1977 (Stanton & Pickard 1981). Stanton (1984, 1986) and Stanton and Pickard (1981) have suggested that the surface salinities in Doubtful Sound are lower than in other fiords since they are affected by the discharge from the Manapouri Power Station, but a survey by Batham (1965) reported summer surface salinities as low as 0 psu close to shore before the power station was built. Station D of Batham (1965) showed surface salinities of 6–12 psu increasing to 17 psu at 10 ft (3 m) and was very close to Tricky Cove, where the present instrument array was moored.

The underwater light regime of the fiords is unknown, although light levels have been subjectively reported as being very low (Grange *et al.* 1981; Grange 1990). The light climate may be at least partly responsible for the general paucity of macroalgal beds and for the colonisation of many unusual invertebrate and fish species (Grange, in press). The depths corresponding to 81%, 33%, 18%, 8%, and 1% of submarine surface irradiance, as well as actual irradiance values, have been published for shore-normal transects off the west coast of South Island, north of Fiordland (Baldwin 1985). Water in this area is influenced by river discharge and high sedimentation, so the results may not be directly applicable to the fiord environment.

Previous studies have not reported daily or monthly variability in physical parameters, except over a short period in February 1969 in Dusky Sound (Jillett & Mitchell 1973). Variability in water properties is likely to be influenced by storms, seasonal climatic changes and, in the deep basins, by seasonal and non-seasonal changes associated with deep-water renewal processes (Stanton 1984).

Large populations of the long-lived antipatharian black coral *Antipathes fiordensis* occur throughout the fiords (Grange 1985). These animals secrete a hard, permanent skeleton, composed largely of chitin and protein, displaying major and minor growth rings (Goldberg, in press). As an aid to understanding the environmental conditions under which these growth rings are laid down, an instrument array was moored in Doubtful Sound at a site for long-term monitoring of *A. fiordensis* populations where C^{14}-labelled compounds were incorporated into the skeleton of growing *A. fiordensis* colonies in February and July 1987.

Outputs from the instruments have provided a 19-month record of physical parameters at the site, including seasonal, daily, and hourly variability at different depths, that may be compared with previous oceanographic data that have been collected sporadically, over shorter periods of time.

Physical oceanographic processes are reasonably well understood in the fiords following the above studies, but short-term variability, fine-scale changes in parameters associated with the halocline, and correlations between meteorology and underwater irradiation, temperature, and salinity have not been reported previously. This report presents the data from the instruments, as daily means, and monthly means for all parameters.

METHODS

The environmental monitoring array (EMA) was moored in Doubtful Sound at Tricky Cove (45°20.95'S, 167°02.83'E), approximately mid-way down the fiord from Deep Cove (Fig. 1). The instruments consisted of three TBI Model 415 conductivity meters, three LICOR 1000-15 temperature probes, and a LICOR LI-192SA underwater quantum sensor, all connected by waterproof cables to a LICOR LI-1000 datalogger, situated above high tide. A LICOR LI-190SA surface quantum sensor was also connected to the datalogger (Fig. 2). Both quantum sensors had a spectral response of 400–700 nm.

EMA was originally deployed on 24 November 1987, with the sensors moored at the following depths below MHW (Fig. 3).

1. Temperature probes at 4 m, 7 m, and 15 m.
2. Conductivity probes at 4 m, 7 m, and 15 m.
3. A quantum sensor at 9 m, suspended with the sensor facing vertically toward the surface, below a small buoy approximately 10 m out from the rock face to avoid excessive shading.
4. A surface quantum sensor, tied to a branch of a tree, facing vertically upward, and not shaded by vegetation.

These depths were chosen because previous observations had indicated a sharp halocline at a depth of around 3–4 m for most of the year, although the depth of the low-salinity layer could extend a few metres below this during periods of heavy and constant rain. The sensors at 4 m were therefore chosen to reflect the

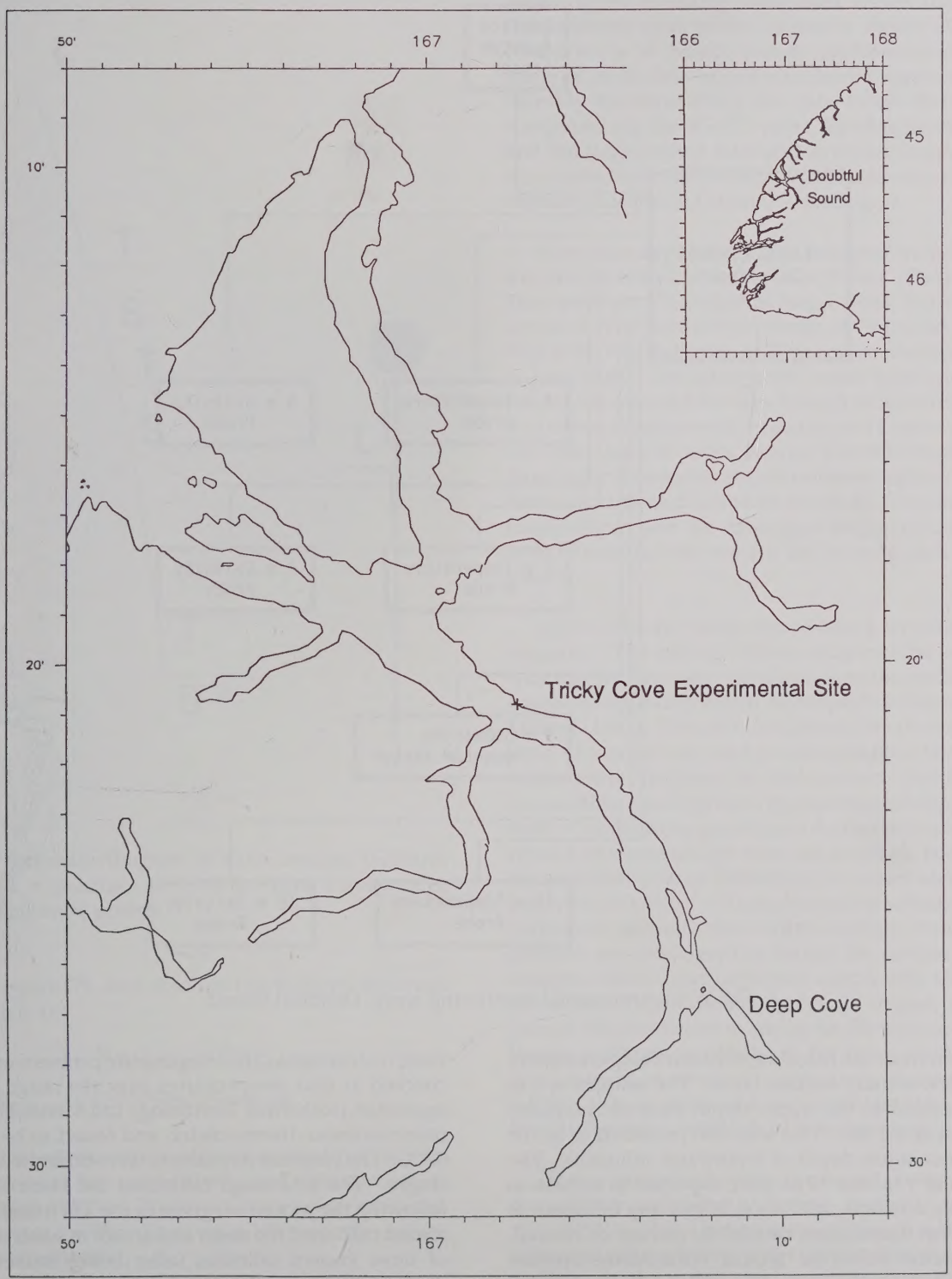

Fig. 1. Doubtful Sound, New Zealand, showing the site at Tricky Cove where EMA was deployed from November 1987 to June 1989.

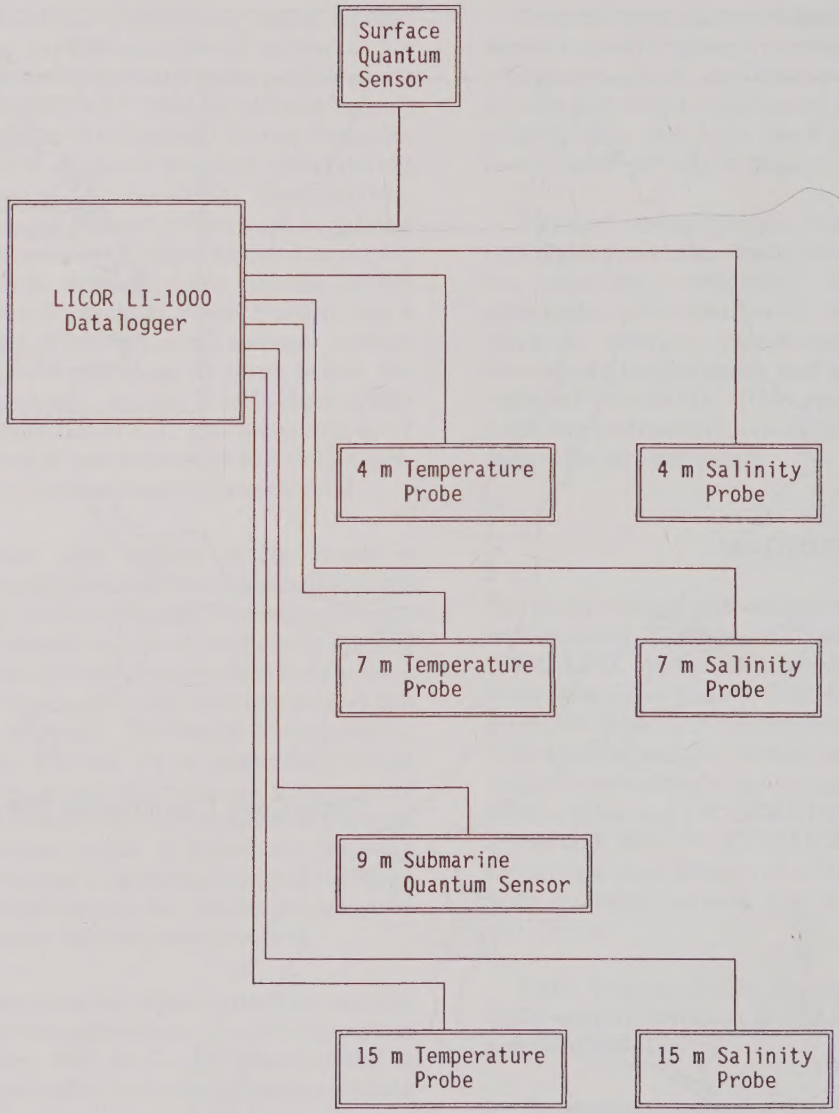

Fig. 2. Environmental monitoring array, Doubtful Sound.

conditions near the halocline, without being constantly in the low-salinity surface layer. The sensors at 7 m corresponded to the upper depth limit of *Antipathes fiordensis* at the site. This was also predicted to be the likely maximum depth of freshwater influence. The sensors at 9 m and 15 m were expected to remain in relatively constant conditions, below any influence of short-term fluctuations caused by climate or rainfall, and therefore reflect the "typical" fiord marine environment.

The quantum sensors were supplied with calibration certificates and no other calibration was performed on these instruments. The temperature probes were spot-checked at four temperatures over the range 5–20°C against an Isothermal Technology Ltd Model 909 platinum resistance thermometer, and found to be within 0.1°C. The conductivity meters were calibrated in two stages. The first stage calibrated the electronics by following the procedure given in the TBI manual. The second calibrated the meter and sensor in water samples of three known salinities (after being immersed in deionised water and set to zero), and was compared with a Guildline Autosal Model 8400A laboratory salinometer. UNESCO routines were used to determine conductivity ratios from salinity (S), temperature (T)

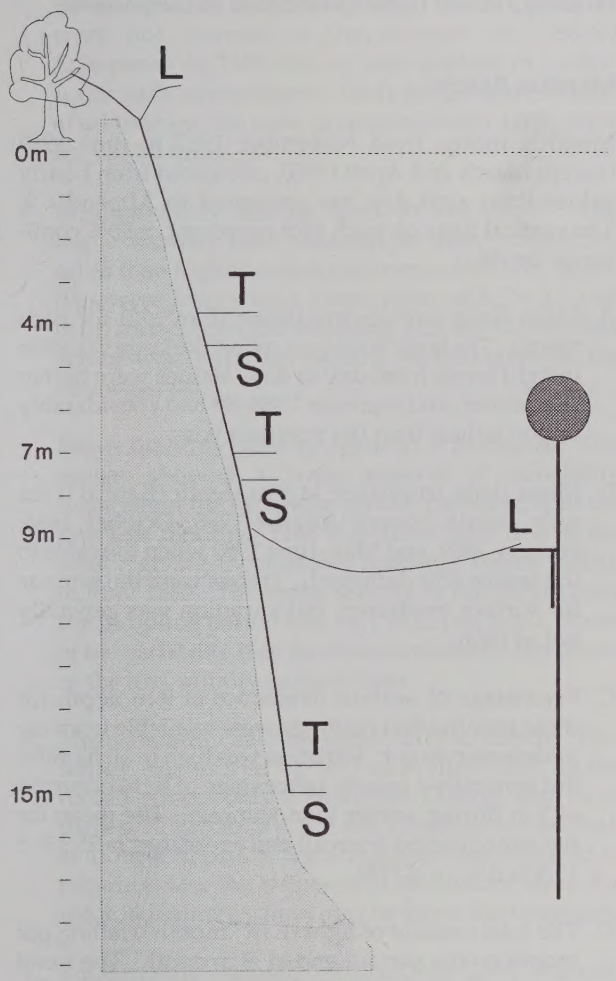

Fig. 3. Schematic diagram of EMA sensors, Doubtful Sound. L = quantum sensors; S = conductivity cells; T = temperature probes.

and pressure (P), and absolute conductivity was then calculated as :

$$R = C_{(S.T.P.)} / C_{(35,15,0)}$$

where $C_{(35,15,0)}$ = 42.9225 milliSiemens.

All meters were then adjusted to read the same as the Autosal at this conductivity, and then spot-tested at two other salinities. There was some variation between the metres at lower conductivities, but no further adjustments were made.

The datalogger was programmed to read for 1 minute every 5 minutes, and log values hourly from all sensors. Instantaneous quantum values ($\mu E.m^{-2}.s^{-1}$) were logged as hourly integrated values ($E.m^{-2}.h^{-1}$), temperatures were stored as hourly means (°C), and conductivity as hourly means (milliSiemens). The memory of the data-logger was cleared approximately monthly by transferring the data to an IBM laptop computer, via the RS-232 port. Datalogger batteries and the large, sealed lead-acid batteries connected to the conductivity cells were also replaced each time the memory was cleared from the datalogger.

Soon after deployment, the temperature probes at 4 m and 15 m leaked and were replaced. The temperature probe at 7 m failed in March 1988, but was not replaced. The conductivity probe at 7 m failed during May 1988, and the probe at 15 m was moved up to 7 m in June 1988. The cable to the underwater quantum sensor was abraded through several times throughout the period of deployment, caused by wave action moving the cable against rocks around low-tide level. The datalogger developed an intermittent malfunction in February 1988 and had to be removed. The fault was finally traced and the datalogger redeployed in May 1988. These factors explain the missing data on the graphs.

Light levels and temperature values are considered accurate. The salinity values may not be accurate because they have been calculated from the conductivity values, using an algorithm developed by Fofonoff and Millard (1983). This calculation requires the incorporation of temperature and pressure values, but where temperature readings at the correct depth were unavailable, readings from the next closest depth were used. Conductivity readings at 4 m were disregarded when 4-m temperatures were not available because of the potentially large differences in water above and below the halocline. Although absolute salinity values may not be accurate, the relative readings, trends, and patterns are considered to reflect the environmental changes. EMA was deployed specifically to follow environmental conditions that could trigger or affect growth-ring formation in *Antipathes fiordensis* and since these conditions are likely to be either catastrophic (e.g., during storms) or cyclic (e.g., seasonal) the salinity values presented are considered to be sufficiently precise to identify such occurrences.

Hourly integrated surface quantum readings were included for analysis only during daylight i.e., when $> 1 \times 10^{-4}$ $E.m^{-2}.h^{-1}$. Underwater readings less than this value and submarine readings greater than the surface readings at the same time were disregarded. This prevented the inclusion of spurious values associated with seawater seepage into the cable. During summer months, however (typically between 1100 h and 1300 h,

from November to February), the positions of the two sensors allowed direct sunlight to reach the submarine sensor while the surface sensor was still in shade. During these periods, the underwater readings were not disregarded if greater than surface readings. The percentage of surface light at 9 m was calculated from each pair of hourly values, not from daily means of surface and submarine irradiance.

The filtered raw data resulted in a masterfile of 10 897 records (a copy is available from the authors), and were transformed by a program called EMAMEAN written in Modula–2 by one of us (RJS). This program presented data from the masterfile as hourly values, or as calculated means over one or more days, or one month, between any dates, which allowed patterns to be examined over different time scales.

A copy of the meteorological data from Deep Cove over the same period that EMA was deployed was obtained from the Department of Conservation, Te Anau. Daily air temperatures (taken at 0800 h) and daily rainfall were recorded during the periods when DOC staff were stationed at the Deep Cove hostel. Total daily rainfall and mean daily temperatures, averaged over the same periods as the EMA outputs, were calculated using a modified EMAMEAN program.

RESULTS

Daily Results

Daily means for all parameters for each month from 1500 h, 24 November 1987, to 1400 h, 8 June 1989 (excluding March and April 1988 when the datalogger malfunctioned), are presented in Appendix 1. Each month contains eight separate plots —

A. Mean daily irradiance ($E.m^{-2}.h^{-1}$), at the surface and 9 m, calculated from hourly values.

B. The percentage of surface light at 9 m depth.

C. The total daily irradiance ($E.m^{-2}.d^{-1}$) at the surface and 9 m depth.

D. The percentage of the total daily irradiation at 9 m depth.

E. Mean daily water temperature (°C) at 4 m, 7 m, and 15 m, calculated from hourly values.

F. Mean daily salinity (psu) at 4 m, 7 m, and 15 m, calculated from hourly conductivity values.

G. Daily air temperature (°C) as recorded at Deep Cove, at the head of Doubtful Sound, approximately 10 km from Tricky Cove.

H. Daily rainfall (mm) as recorded at Deep Cove.

Monthly Results

Monthly means from November 1987 to June 1989 (except March and April 1988), calculated from hourly values from each day, are presented in Appendix 2. The vertical lines on each plot represent ± 95% confidence limits.

A. Mean daily surface irradiance ($E.m^{-2}.d^{-1}$) for each month. The large error bars reflect the large variation in light levels from day to day. Values were higher in summer, and summer 1988–89 had considerably higher values than the previous year.

B. Mean daily irradiance at 9 m depth ($E.m^{-2}.d^{-1}$) for each month, except August 1988, October 1988, January 1989, and May–June 1989 when the cable to the sensor was damaged. Trends were the same as for surface irradiance, but variation was generally not as high.

C. Percentage of surface irradiance at 9 m depth for those months that readings were available from the underwater sensor. Variation was high in all months, but generally a greater percentage of light occurred at 9 m during winter than summer. The mean for the entire period from all daily readings is 25.3% ± 15.5 (s.d.); (n = 176).

D. The total amount of light ($E.m^{-2}.month^{-1}$) falling per month on the surface and at 9 m depth. The trend was similar to the mean daily irradiance curves.

E. Mean monthly water temperature (°C) at 4 m depth. As expected, the water was warmer in summer than winter, with a maximum in February and a minimum in September.

F. Mean monthly water temperature (°C) at 7 m depth. This sensor leaked and did not function after February 1988, but the results until then showed a close correlation with temperatures at 4 m.

G. Mean monthly water temperature (°C) at 15 m depth. This sensor failed soon after installation and was replaced in May 1988. The curve was very similar to that from 4 m, and variability was much lower during winter months, as indicated by the smaller confidence limits.

H. Mean monthly air temperature (°C) at Deep Cove. The curve showed a clear seasonal trend, similar to

the underwater sensors, although air temperatures were not warmer in the summer of 1988–89 (compared to 1987–88), as was evident in underwater daily temperatures. Daily temperatures varied at all times of the year, giving relatively large error bars at all times.

I. Mean monthly salinity (psu) at 4 m depth. The curve showed little seasonal or daily variability, other than higher values in summer 1987–88. Salinities were low, with a mean value of 8.5 ± 2.3 psu (s.d.) throughout the sampling period. Clearly this sensor was in the low-salinity surface layer for the entire period.

J. Mean monthly salinity (psu) at 7 m depth. The sensor showed a large amount of variability throughout the sampling period, particularly in the first few months. This may have been due to the sensor giving inconsistent readings, before failing in May 1988. The mean salinity at this depth over the sampling period was 16.1 ± 6.2 psu (s.d.). Some of the variability may have been caused by intrusions of the low-salinity surface layer.

K. Mean monthly salinity (psu) at 15 m depth. This sensor was moved up to 7 m in June 1988, so the record covers only 4 months. During that time, there was variability, but the values remained high at around 30 psu. Since this sensor was expected to remain below the influence of the surface layer, the recorded salinity values may be lower than expected.

L. Total monthly rainfall (mm) at Deep Cove. Rain fell in all months, but a clear peak occurred from August to October 1988. Throughout the entire sampling period, a total of 9728.7 mm of rain fell, with an average of 486.4 $mm.month^{-1}$. This translates to an annual rainfall of 5837 mm, very close to the mean annual rainfall of 5290 mm, reported by Stanton and Pickard (1981).

Present Results Compared with Long-term Means

Stanton (1986) presented results of mean monthly air temperatures for Milford Sound for the period 1934–1980, and sea-surface temperatures at Anita Bay near the entrance to Milford Sound for the period 1979–83. These have been plotted with the mean monthly air temperatures at Deep Cove and water temperatures at 4 m and 15 m depth at Tricky Cove obtained from this study, and are given in Appendix 3.

Air temperatures obtained during this study showed a very similar curve to the long-term means, with maximum values in January–February and minimum values in June–July. Throughout the sampling period the temperatures at Deep Cove appeared slightly lower than those from Milford Sound. This could reflect a cooler year than normal, but it is more likely to reflect the locality; Deep Cove is approximately 100 km further south, and further into the mountains, since Doubtful Sound is 32 km long whereas Milford Sound is only 16 km long.

The water temperatures also showed similar curves, except during the summer of 1988–89 when Doubtful Sound was significantly warmer. Water temperatures at 4 m in Doubtful Sound were significantly lower in winter 1988 compared to the long-term means. This is likely to be a reflection of the stronger influence of colder freshwater runoff in Doubtful Sound, possibly increased by Lake Manapouri water being discharged from the power-station tailrace. The Milford Sound temperatures were taken at the entrance to the fiord where the surface water was likely to be more saline, to reflect coastal temperatures, and be less influenced by runoff.

Mean monthly water temperatures at 4 m and 15 m, Doubtful Sound, compared with long-term means at Milford Sound showed that the higher-salinity water at 15 m depth had a very similar curve to the surface water at Milford Sound. A comparison of the two depths in Doubtful Sound also showed that surface temperatures were warmer in summer and cooler in winter, reflecting the influence of freshwater runoff.

DISCUSSION

Daily values of all parameters fluctuated throughout all months. Daily irradiance, and the percentage of incident light reaching 9 m below the water surface dropped markedly during days of heavy rainfall. Heavy rainfall also corresponded to sharp decreases in water temperature at 4 m on the same day in winter months, e.g., June, July, and September 1988, and May 1989. This confirms the rapid response of the Doubtful Sound catchment to rainfall, despite the large volumes of water being discharged from the Manapouri Power Station. Interestingly, salinities at 4 m depth, within the low-salinity layer produced by "normal" continuous runoff, were largely unaffected by rainfall, but some decreases at 7 m depth were evident during heavy rain, e.g., October and November 1988. The monthly salinity at 7 m depth and total monthy rainfall plots (Appendix 2, Figs J, L) showed an inverse relationship, but this is not evident at 4 m.

Summer 1988–89 had considerably higher incident light as well as light at 9 m compared to summer 1987–88 (Appendix 2, Figs A, B). This was also reflected in increased water temperatures at 4 m and 15 m (Appendix 2, Figs E, G). It appears from Appendix 3, Fig. B, that water temperatures in summer 1988–89 were significantly warmer than the long-term averages, but this trend was not reflected in air temperatures.

Surface and submarine irradiance were both high during summer months, as would be expected, but the inverse occurred with the percentage of light reaching 9 m. Maximum penetration of light occurred over winter months when absolute values were lower. This possibly reflects detrital material or phytoplankton populations increasing in warmer, well-lit months, absorbing light underwater.

Jerlov (1976) has given an optical classification of marine waters, based on transmittance of downward irradiance. New Zealand generally lies in Oceanic Type I or II water (Jerlov 1976, Fig. 72) which are characterised as being very clear, and blue. Oceanic Type III water is typical of upwelling areas along the west coasts of most land masses, and Coastal Type 1 is typical of clear coastal water, stained with small amounts of "yellow substance". Figure 4 shows transmittance curves for a range of marine environ-

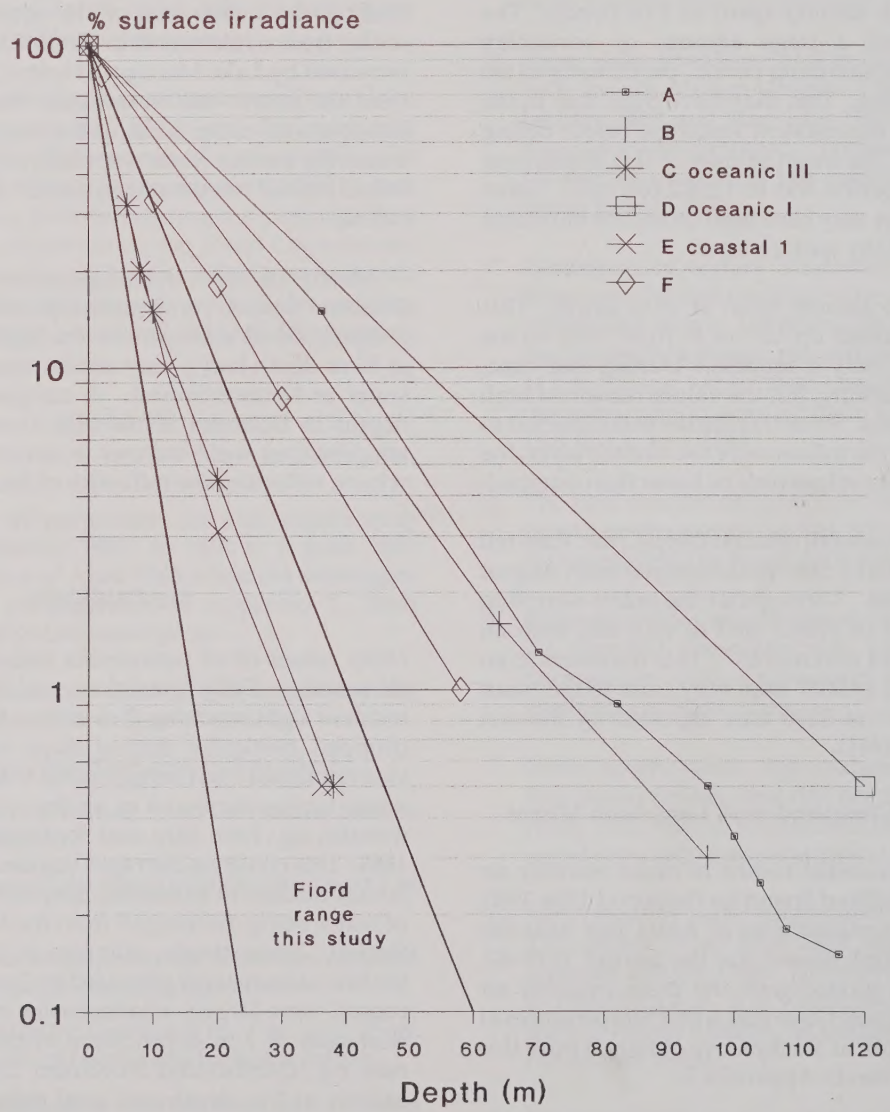

Fig. 4. Light-transmittance curves in various marine environments (see text for explanation). A, after Littler *et al.* (1985); B, after Emson and Woodley (1987); C, D, E, after Jerlov (1970); F, after Baldwin (1985).

ments. Light levels obtained from submersible dives where antipatharian black corals occur in the Bahamas (Littler *et al.* 1985) and Jamaica (Emson & Woodley 1987) show curves similar to the clearest oceanic water, Oceanic Type I of Jerlov (1970). A profile from a typical station off the west coast of South Island, Stn P654, at a depth of 249 m and around 80 km from shore (Baldwin 1985), shows a curve mid-way between Oceanic Type I and Oceanic Type III water, as may be expected on this coast. The range for Doubtful Sound has been plotted on figure 4 by extrapolating the mean transmittance curve from the surface to 9 m (± 1 s.d.), down to the abscissa at 0.1% of surface irradiance. This is an estimate of the transmittance curve since it has been derived from only a single depth, but it indicates that Doubtful Sound water for most of the time may attenuate photosynthetically active irradiation (400–700 nm) similar to Oceanic Type III and Coastal Type 1 waters.

It is generally accepted that 1% of maximum surface illumination is thought to represent the compensation point for marine macroalgae (Ryther 1956). This corresponds to a depth range of 18–40 m in Tricky Cove (Fig. 4), but only a few scattered plants of *Ecklonia radiata* occur at the EMA site, at maximum depths of around 5 m. Although mean values of light penetration at 9 m depth are around 25% of surface irradiance for most of the time, there are several days in each month when light levels at 9 m are below 1%. It appears as though light penetration at Tricky Cove for much of the time is equivalent to very clear coastal or oceanic water, yet algae cannot survive, which is typical of all the New Zealand fiords (Grange *et al.* 1981). A possible explanation is that absolute light levels are very low. It is difficult to obtain a mean value of radiance at 9 m depth, due to the large variation in daily cycles, but the monthly plots show around 0.2 $E.m^{-2}.h^{-1}$ for much of the year, with maximum mean values of 0.9 $E.m^{-2}.d^{-1}$ (Appendix 2, Fig. B). This gives a range of 0.012–0.056 $E.m^{-2}.h^{-1}$ (assuming 16 hours of daylight), which corresponds to instantaneous values of 3.5–15.6 $\mu E.m^{-2}.s^{-1}$. This is less than the value of 5 $\mu E.m^{-2}.s^{-1}$ recorded at 97 m depth off Jamaica by Emson and Woodley (1987), and 100 m depth off the Bahamas by Littler *et al.* (1985), both environments where antipatharians, gorgonians, comatulid crinoids, and asteroschematid ophiuroids exist, and below the level of foliose algal growth. These values normally occur only below 20 m off the west coast of South island, even in summer (Baldwin 1985). The light levels underwater in the New Zealand fiords are very low, possibly below those necessary to sustain large algae, yet the transmittance estimates indicate oceanic conditions. A possible explanation may be found in the nature of the surface layer, which reduces light levels by 20–30%. Light attenuation is associated with the 3-m-thick, low-salinity layer that is stained yellow-brown with "gelbstoff"-fluvic and humic acids (Peake 1978). Particulate matter in the water column is sparse (< 1 $mg.l^{-1}$; Pickrill 1987), thus light absorption, rather than scattering by particles, may be the controlling factor in the process of light attenuation. The marine waters of the fiord have optical properties more consistent with oceanic waters than coastal waters with their characteristically higher sediment loads. The low-salinity surface layer may also possibly affect the wavelength of light below. Although underwater visibility is often 20–30 m in Doubtful Sound, sunlight filtered through the surface layer appears green, and this may be unsuitable for photosynthesis, but the attenuation of different wavelengths needs further examination before this hypothesis can be tested.

Large sudden fluctuations in physical parameters occur in Doubtful Sound at depths were *Antipathes fiordensis* survives. These may act as cues for discontinuities in growth or skeletal deposition that would result in the formation of a growth ring. The clear seasonal cycle in water temperature may help explain major (annual) growth bands, and the decrease in the proportion of light underwater in summer may reflect an increase in particulate material (living or dead) that could be utilised as a food source by the black coral colonies. The sudden decreases in temperature or salinity, or changes in light levels associated with storm events, may help explain the formation of some of the minor rings. Autoradiographic analyses of the growth bands laid down during incubation with C^{14}-labelled compounds, the subsequent growth in pinnule length, and the deposition of growth rings since incubation, may help explain the ecological significance of many of the fluctuations seen in the physical parameters at this site.

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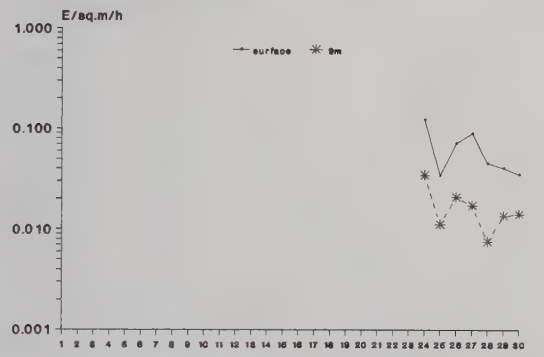
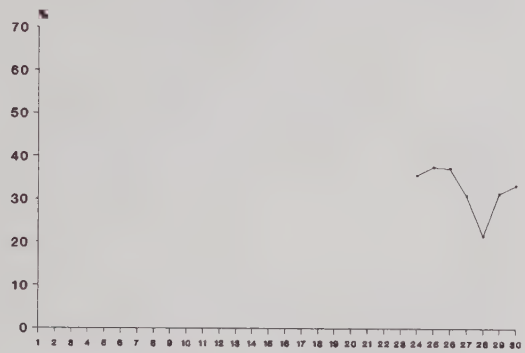
APPENDIX 1. Daily means for all parameters for each month from 24 November 1987 to 8 June 1989.

November 1987

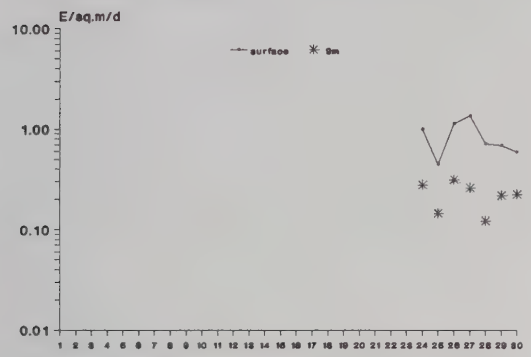
A. Mean daily irradiance



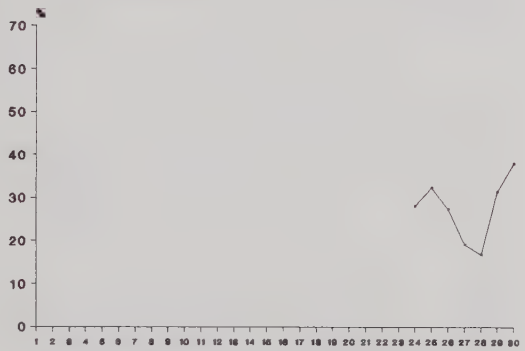
B. % surface light at 9m



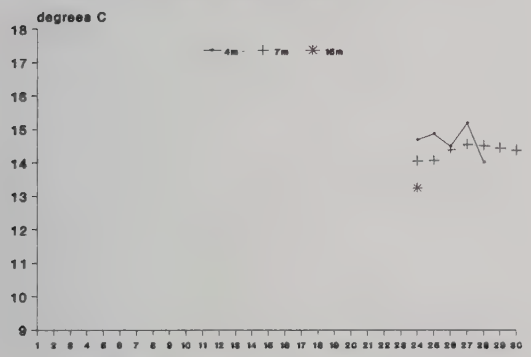
C. Total daily irradiance



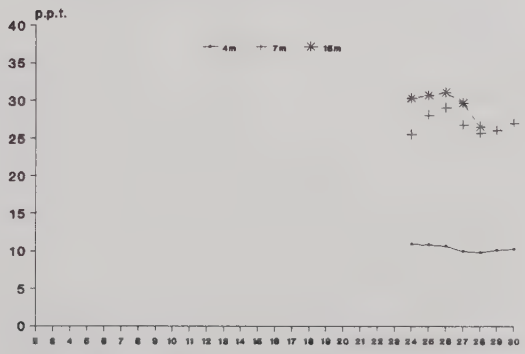
D. % total light at 9m



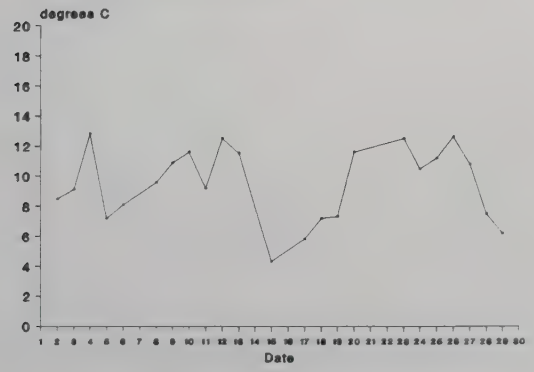
E. Mean daily water temperature



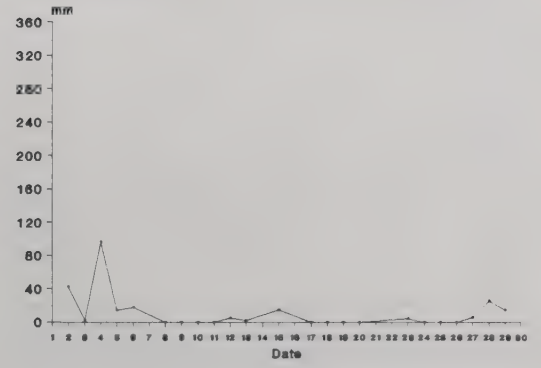
F. Mean daily salinity



G. Mean daily air temperature

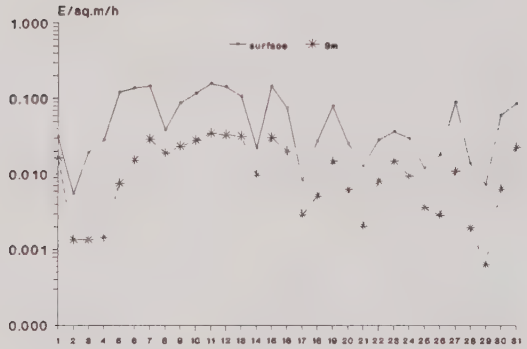


H. Daily rainfall

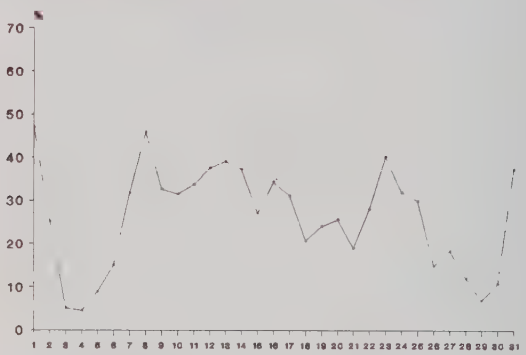


December 1987

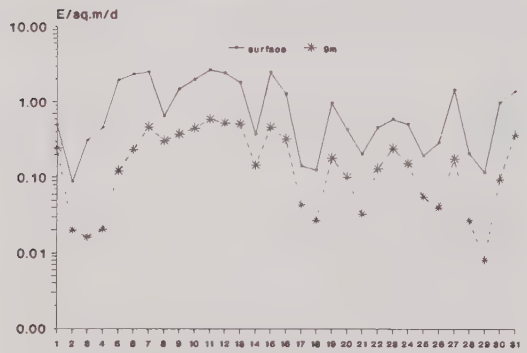
A. Mean daily irradiance



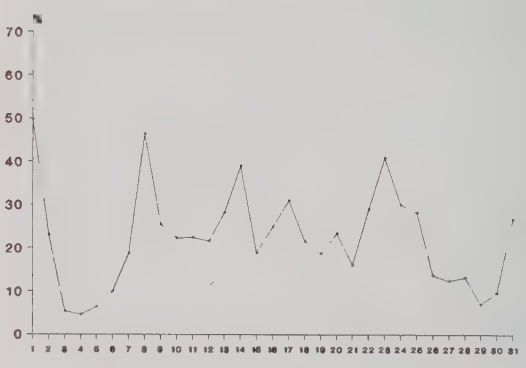
B. % surface light at 9m



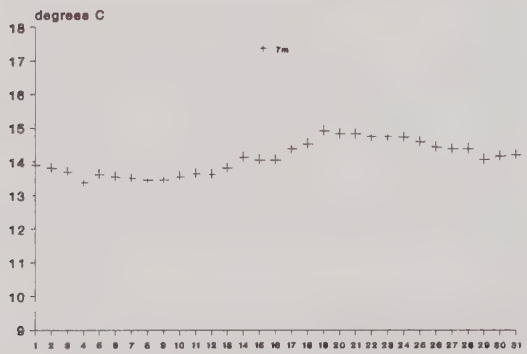
C. Total daily irradiance



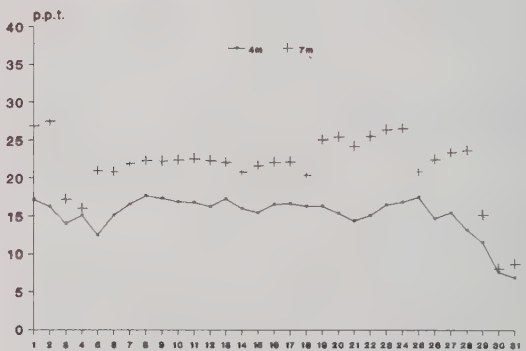
D. % total light at 9m



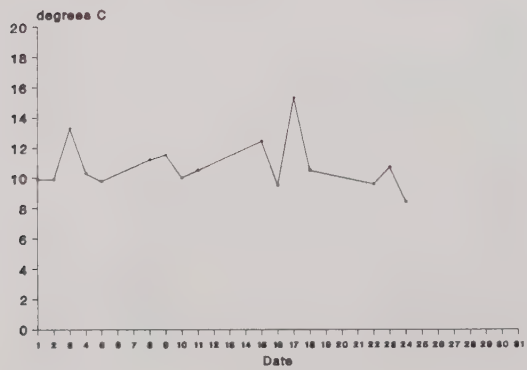
E. Mean daily water temperature



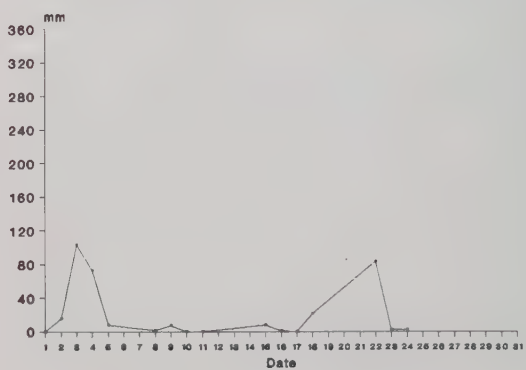
F. Mean daily salinity



G. Mean daily air temperature

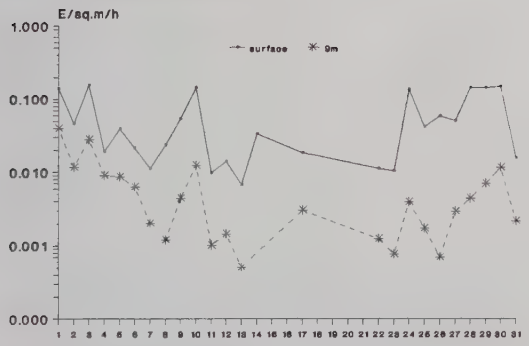


H. Daily rainfall

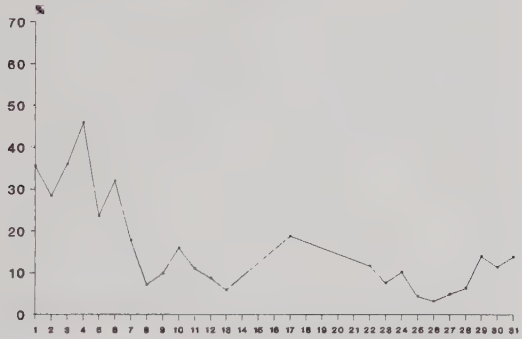


January 1988

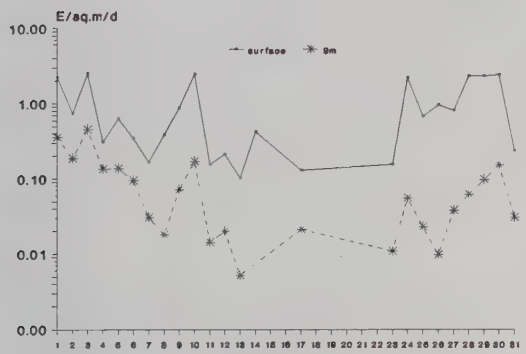
A. Mean daily irradiance



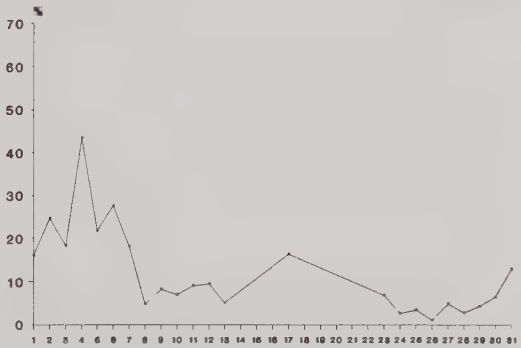
B. % surface light at 9m



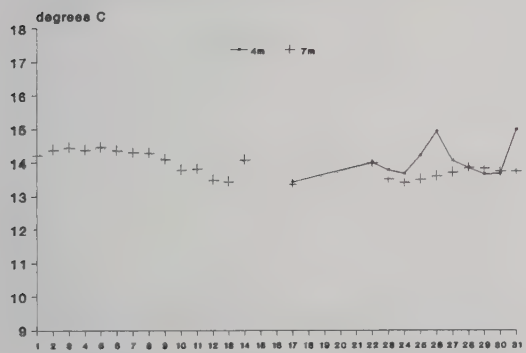
C. Total daily irradiance



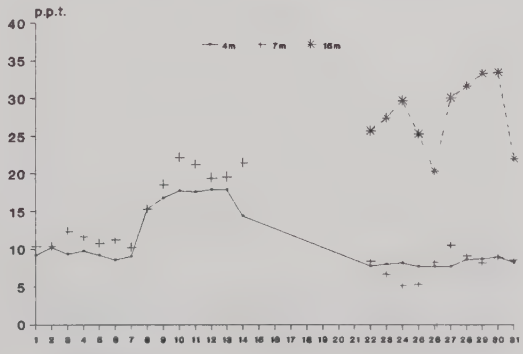
D. % total light at 9m



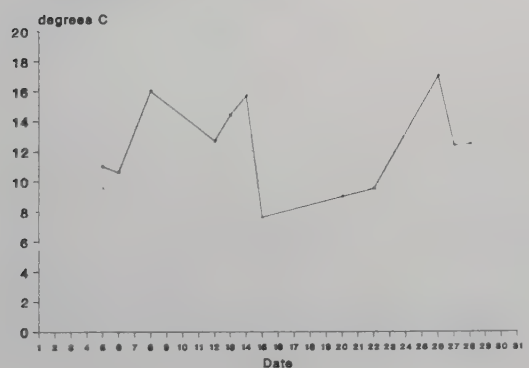
E. Mean daily water temperature



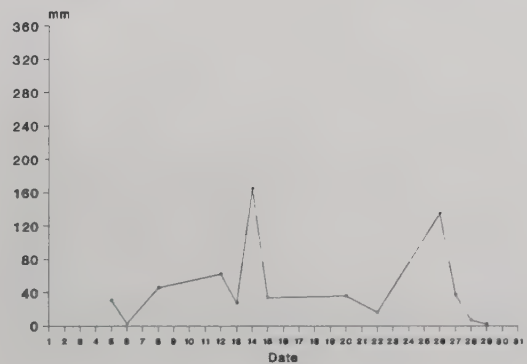
F. Mean daily salinity



G. Mean daily air temperature

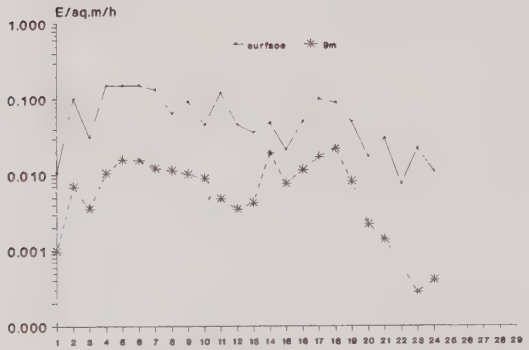


H. Daily rainfall

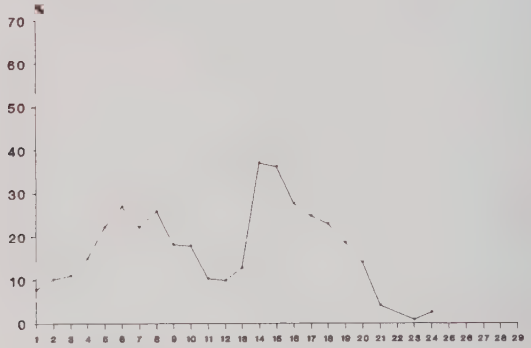


February 1988

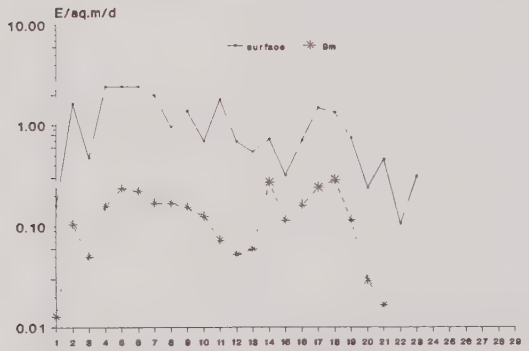
A. Mean daily irradiance



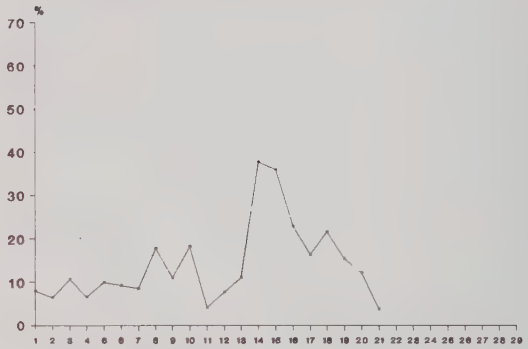
B. % surface light at 9m



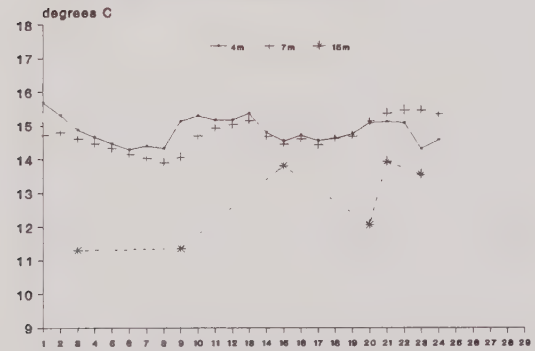
C. Total daily irradiance



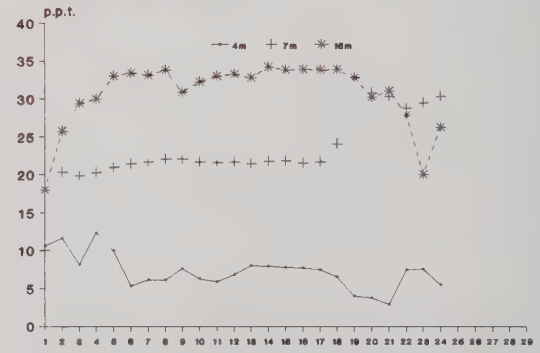
D. % total light at 9m



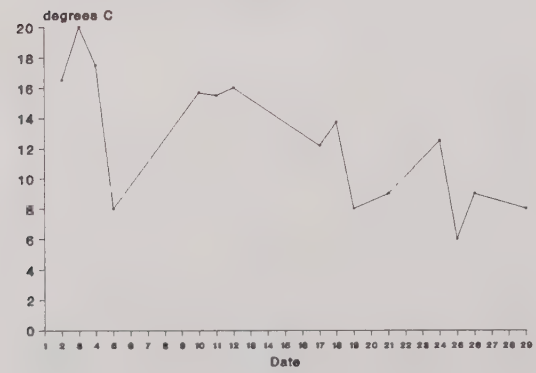
E. Mean daily water temperature



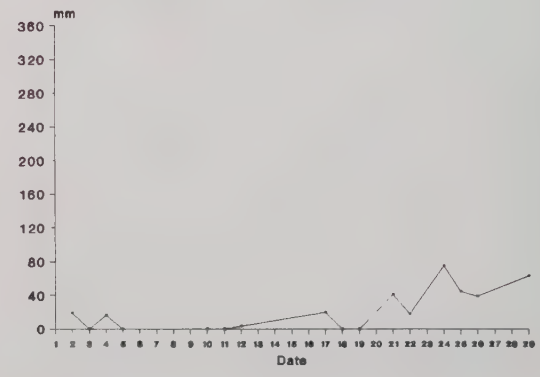
F. Mean daily salinity



G. Mean daily air temperature

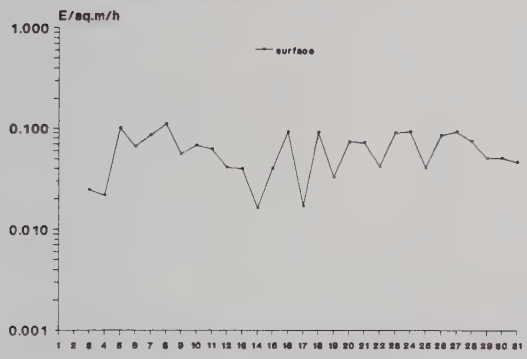


H. Daily rainfall

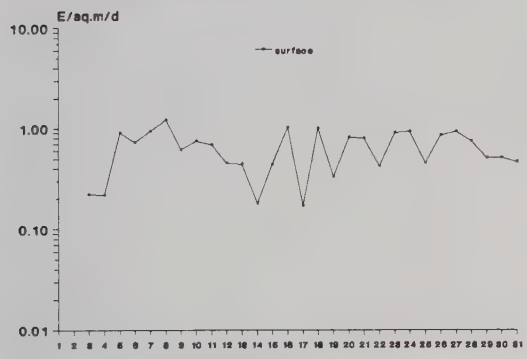


May 1988

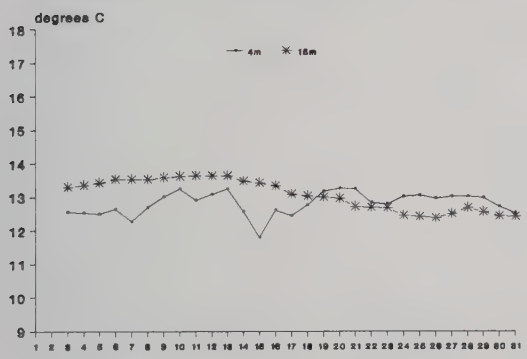
A. Mean daily irradiance



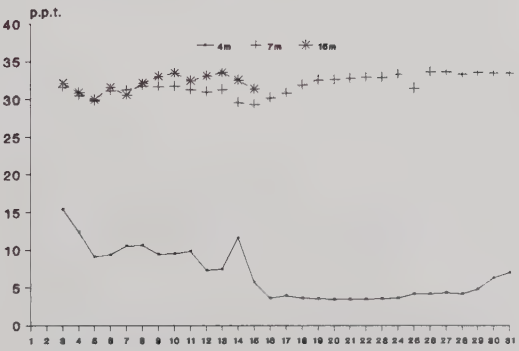
C. Total daily irradiance



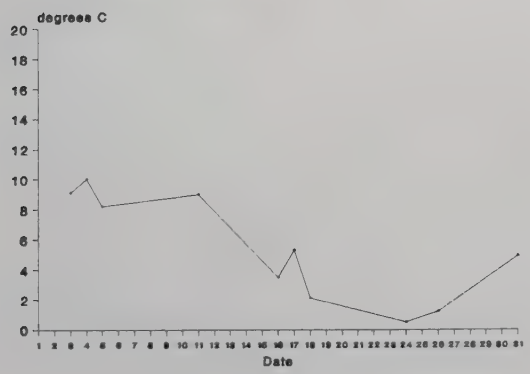
E. Mean daily water temperature



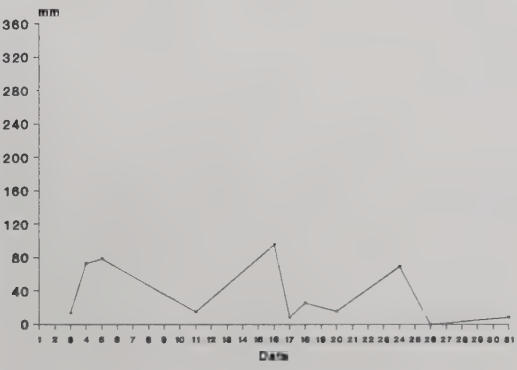
F. Mean daily salinity



G. Mean daily air temperature

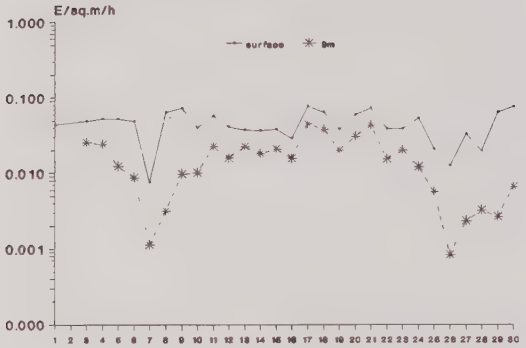


H. Daily rainfall

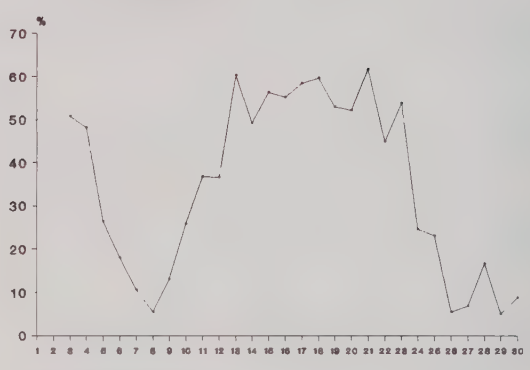


June 1988

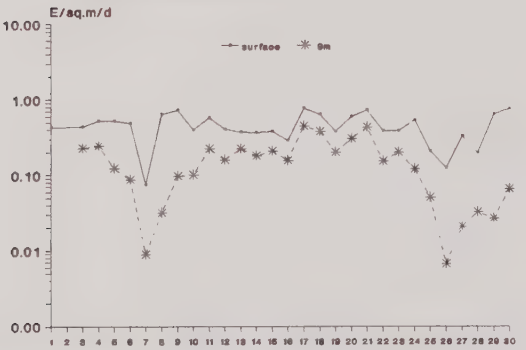
A. Mean daily irradiance



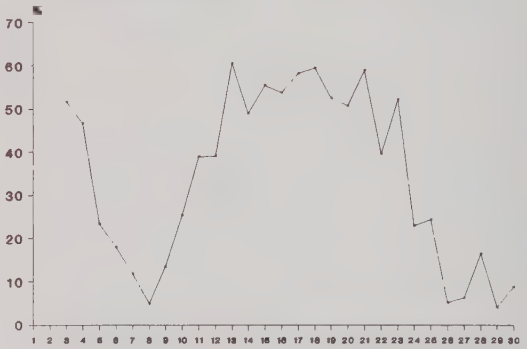
B. % surface light at 9m



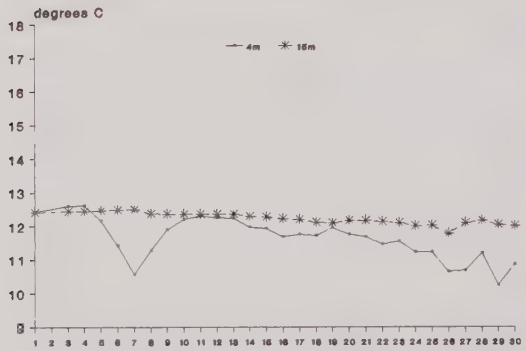
C. Total daily irradiance



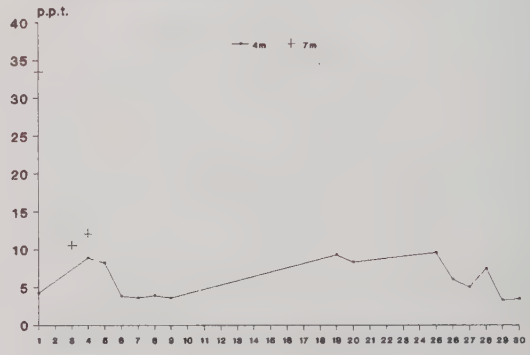
D. % total light at 9m



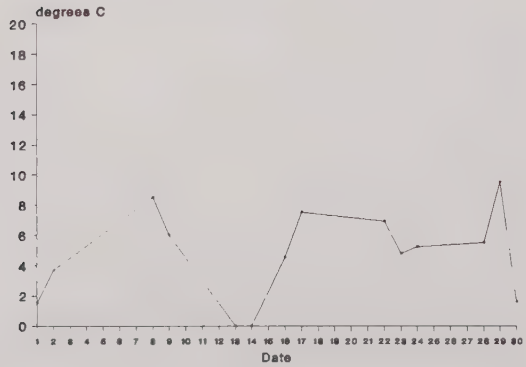
E. Mean daily water temperature



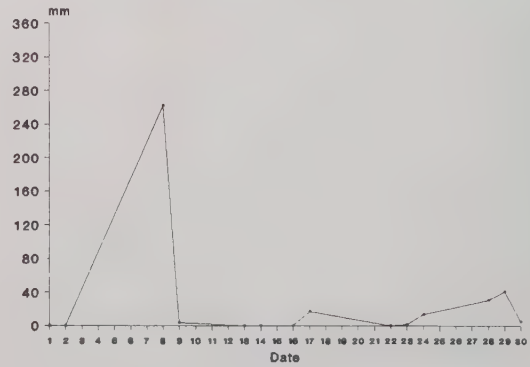
F. Mean daily salinity



G. Mean daily air temperature

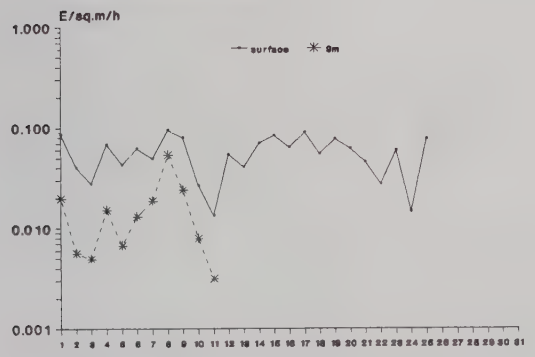


H. Daily rainfall

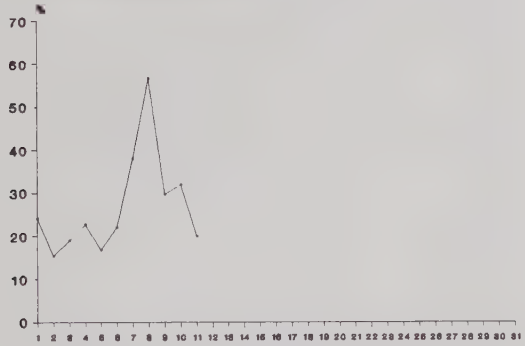


July 1988

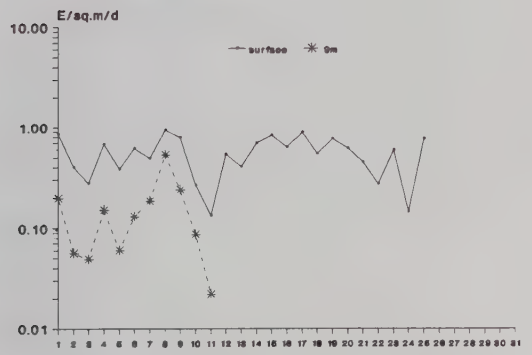
A. Mean daily irradiance



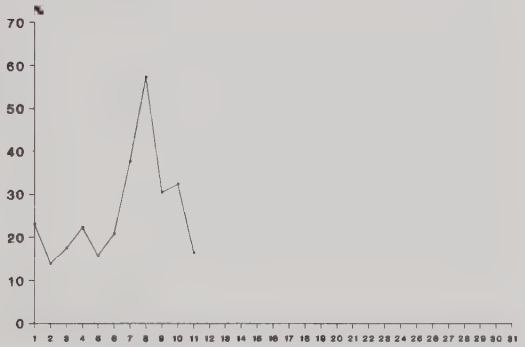
B. % surface light at 9m



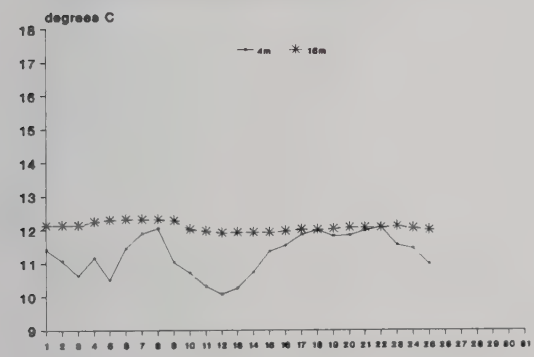
C. Total daily irradiance



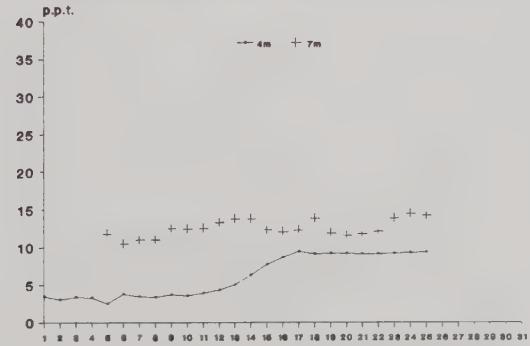
D. % total light at 9m



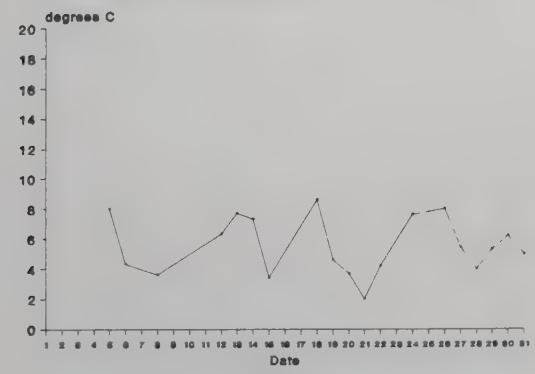
E. Mean daily water temperature



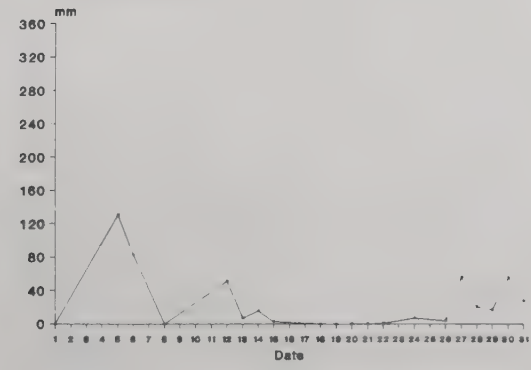
F. Mean daily salinity



G. Mean daily air temperature

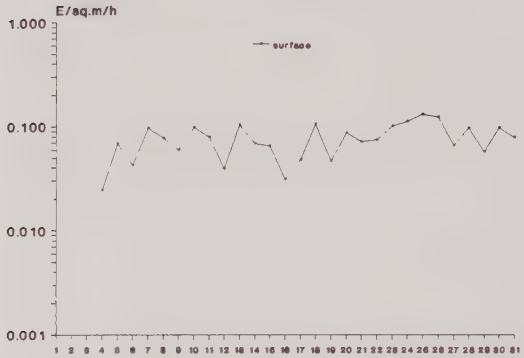


H. Daily rainfall

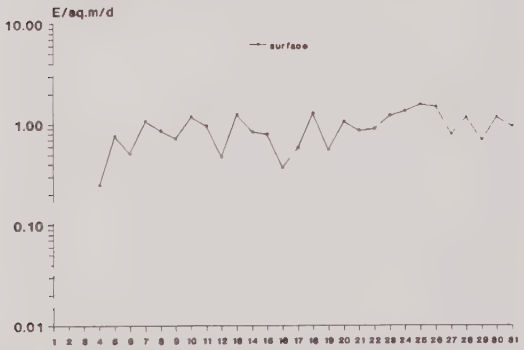


August 1988

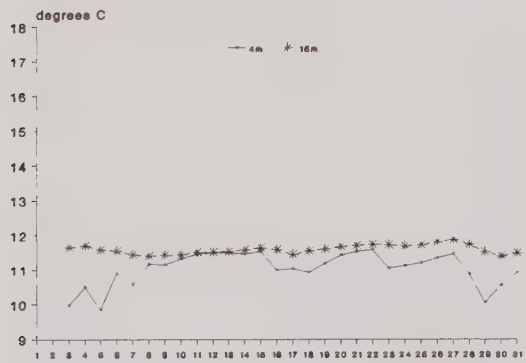
A. Mean daily irradiance



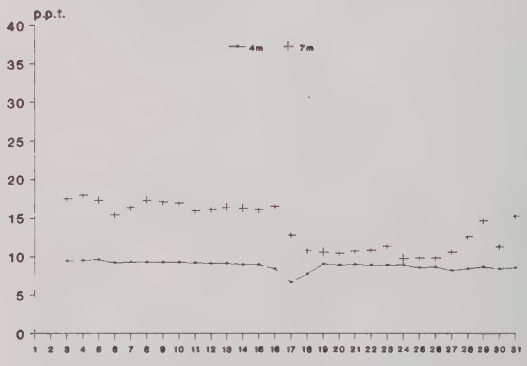
C. Total daily irradiance



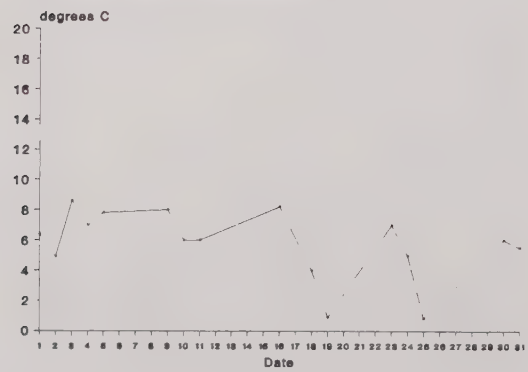
E. Mean daily water temperature



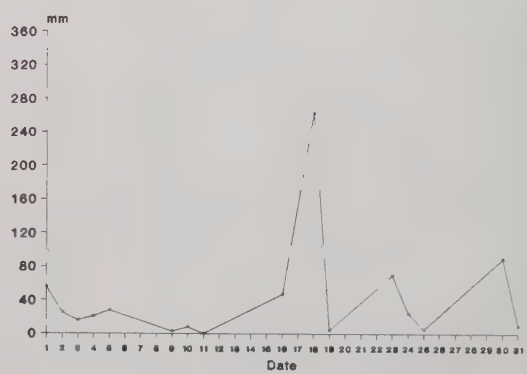
F. Mean daily salinity



G. Mean daily air temperature

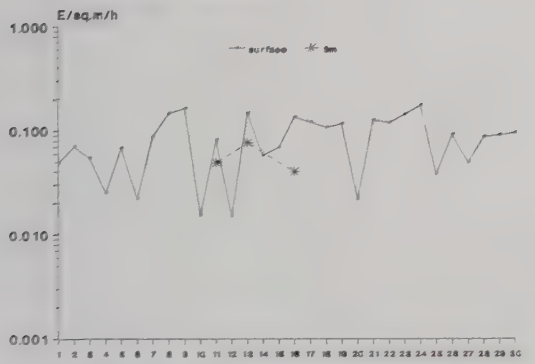


H. Daily rainfall



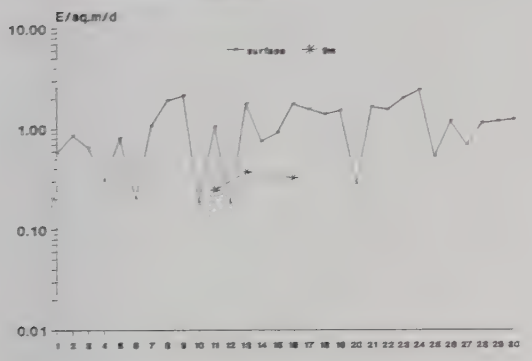
September 1988

A. Mean daily irradiance



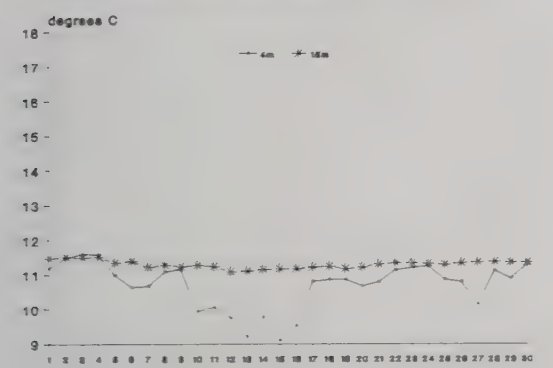
B. % surface light at 9m

C. Total daily irradiance

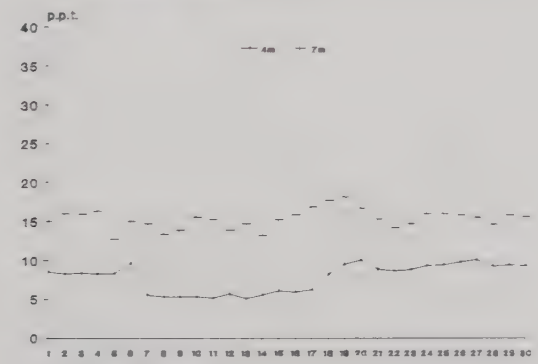


D. % total light at 15m

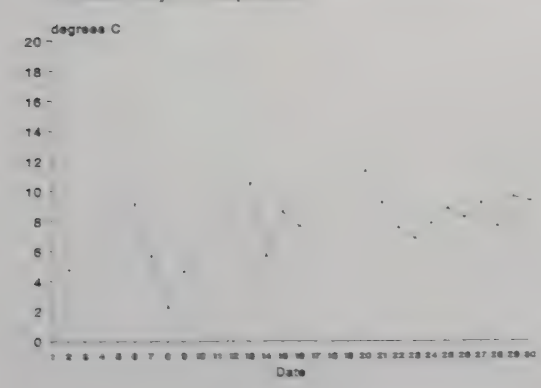
E. Mean daily water temperature



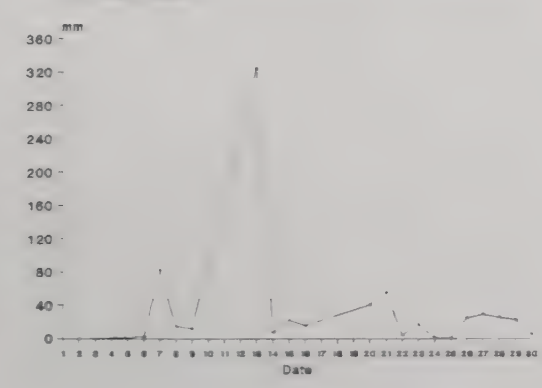
F. Mean daily salinity



G. Mean daily air temperature

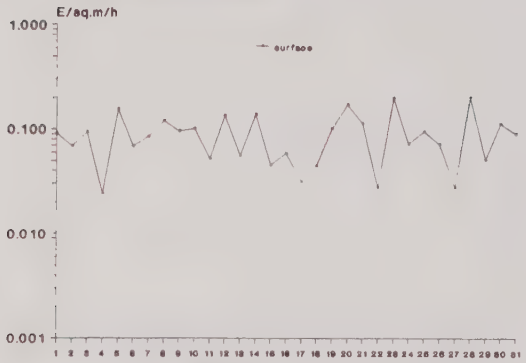


H. Daily rainfall

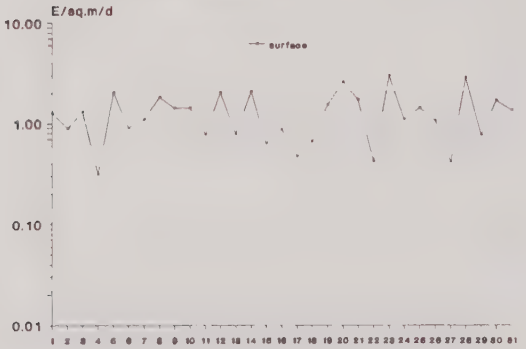


October 1988

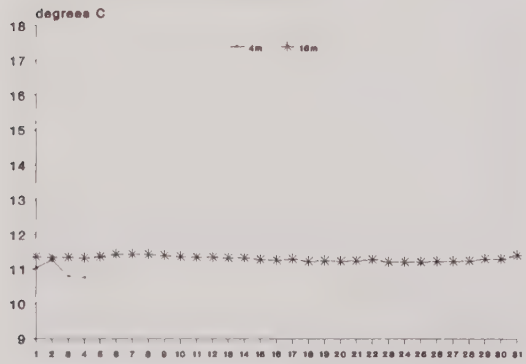
A. Mean daily irradiance



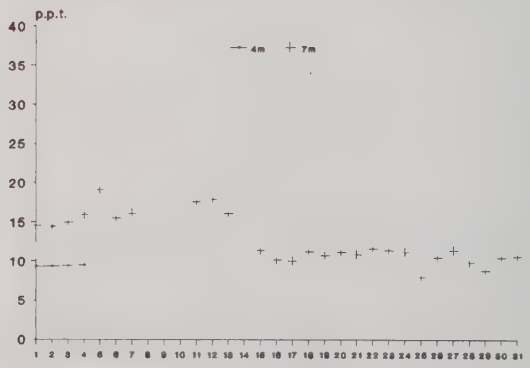
C. Total daily irradiance



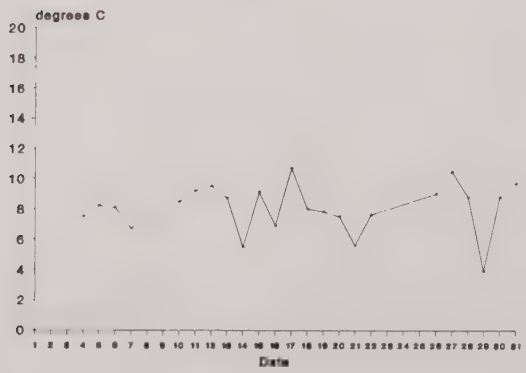
E. Mean daily water temperature



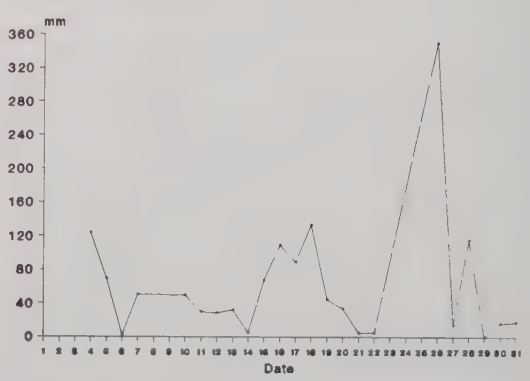
F. Mean daily salinity



G. Mean daily air temperature

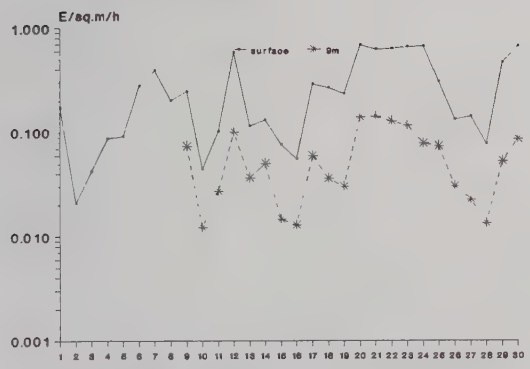


H. Daily rainfall

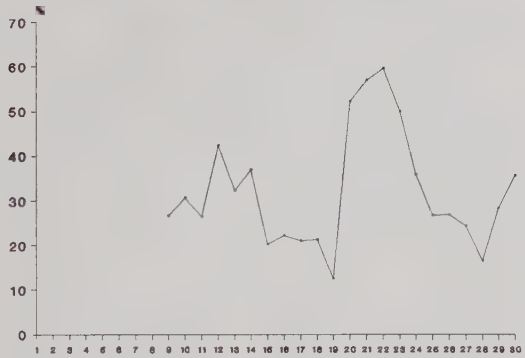


November 1988

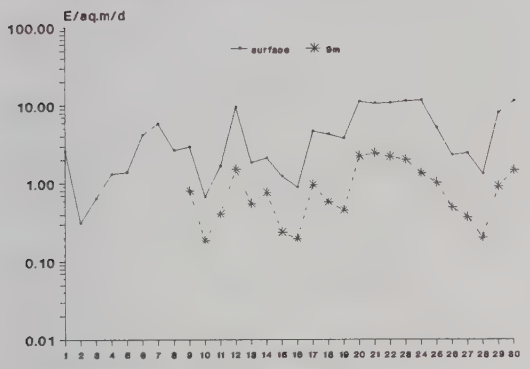
A. Mean daily irradiance



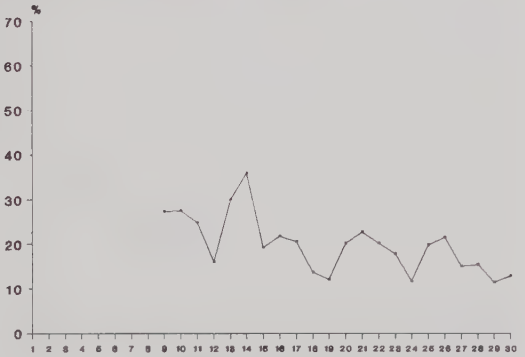
B. % surface light at 9m



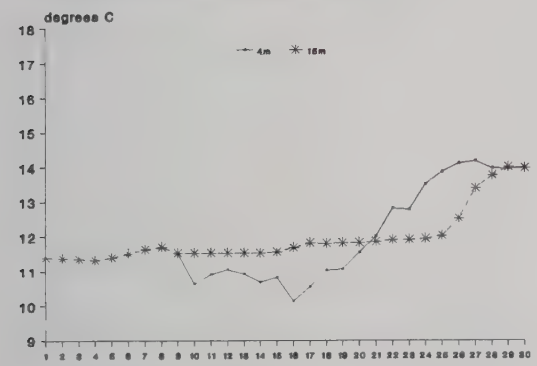
C. Total daily irradiance



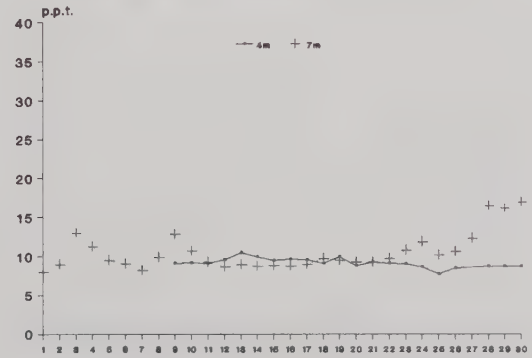
D. % total light at 9m



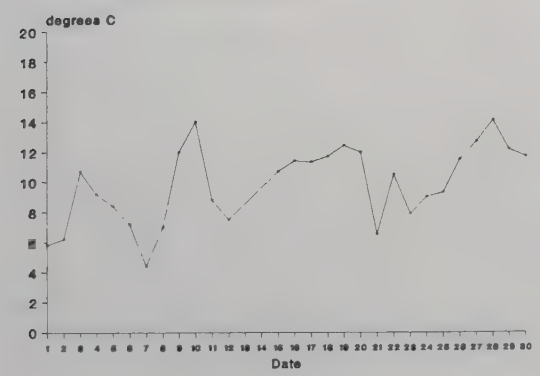
E. Mean daily water temperature



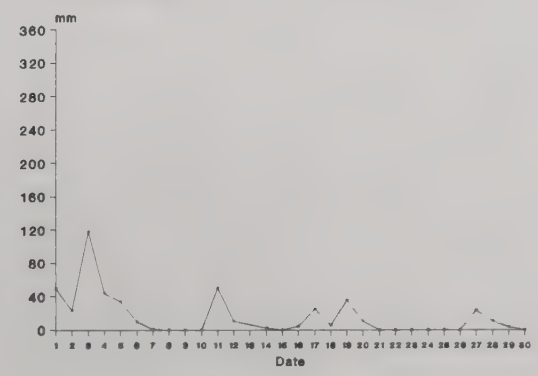
F. Mean daily salinity



G. Mean daily air temperature

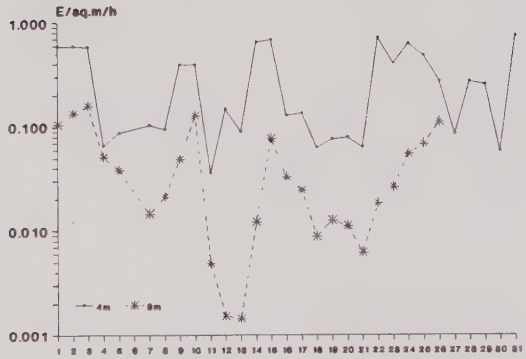


H. Daily rainfall

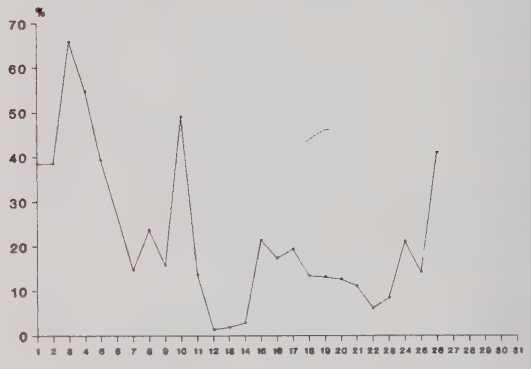


December 1988

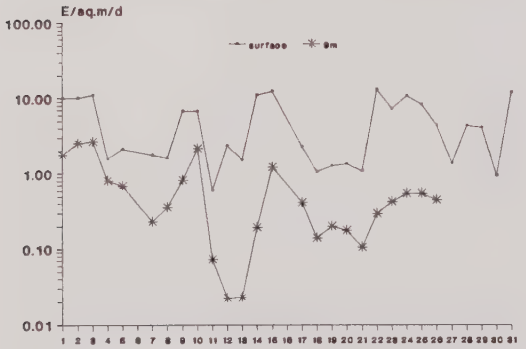
A. Mean daily irradiance



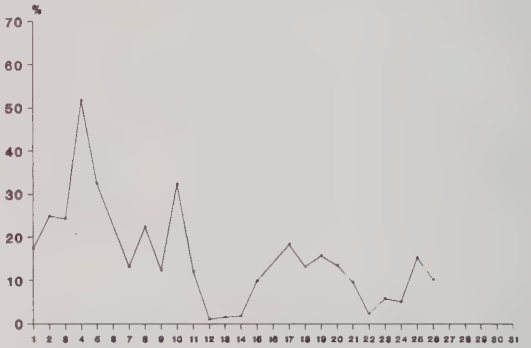
B. % surface light at 9m



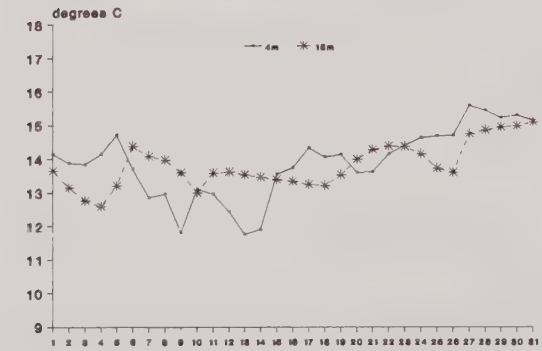
C. Total daily irradiance



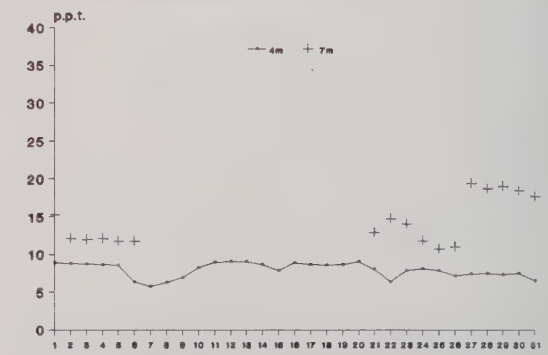
D. % total light at 9m



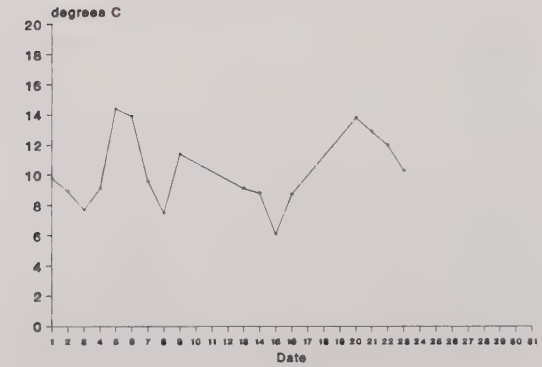
E. Mean daily water temperature



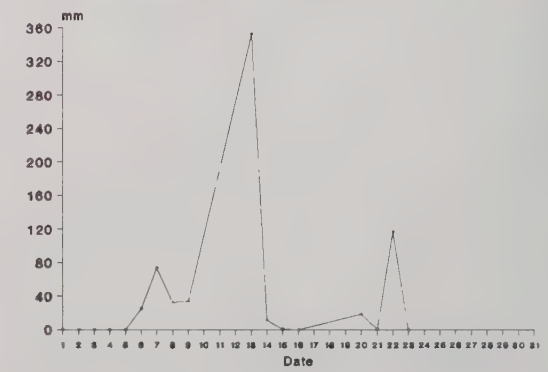
F. Mean daily salinity



G. Mean daily air temperature

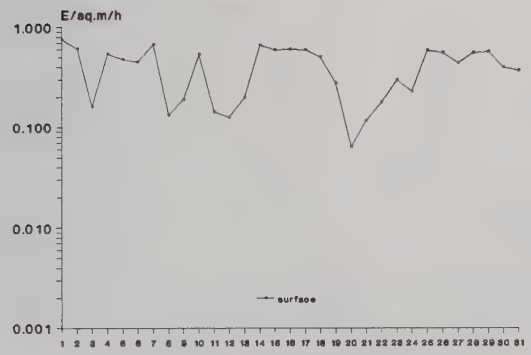


H. Daily rainfall

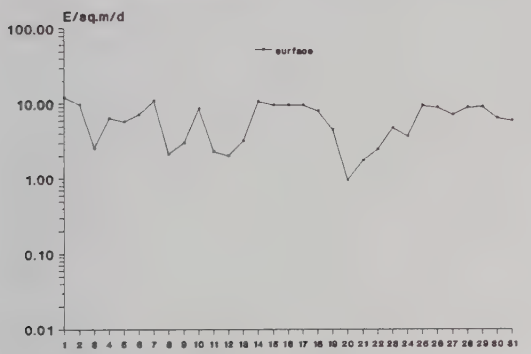


January 1989

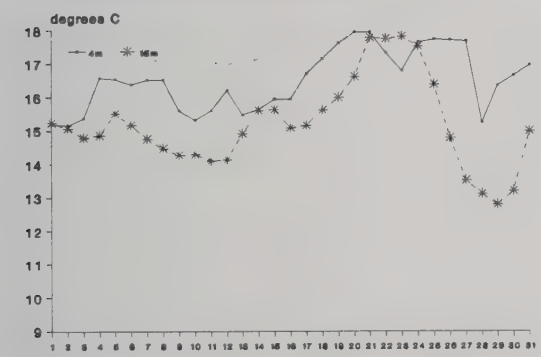
A. Mean daily irradiance



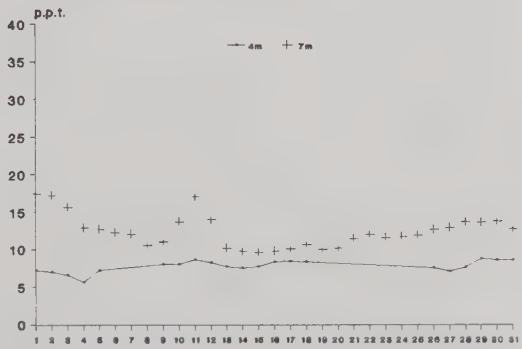
C. Total daily irradiance



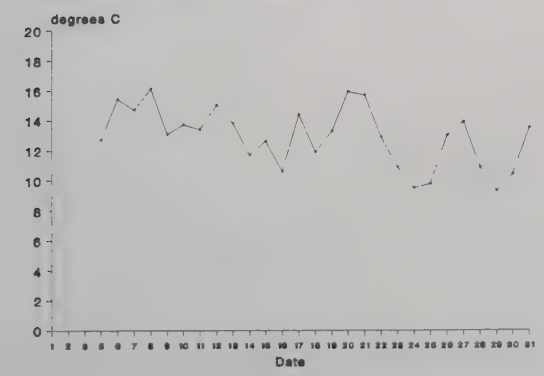
E. Mean daily water temperature



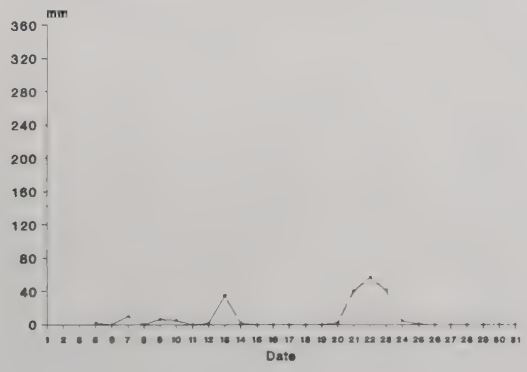
F. Mean daily salinity



G. Mean daily air temperature

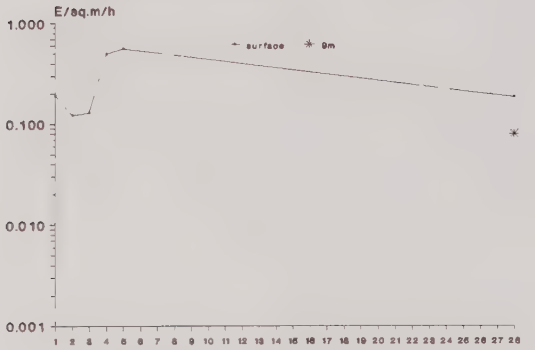


H. Daily rainfall



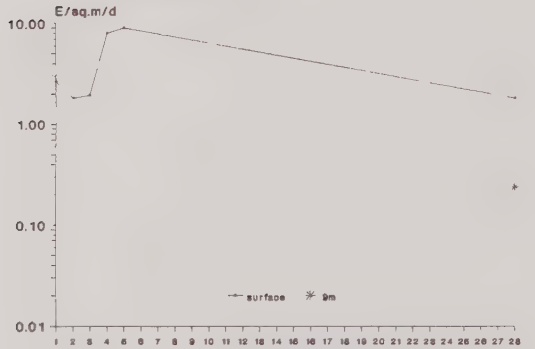
February 1989

A. Mean daily irradiance



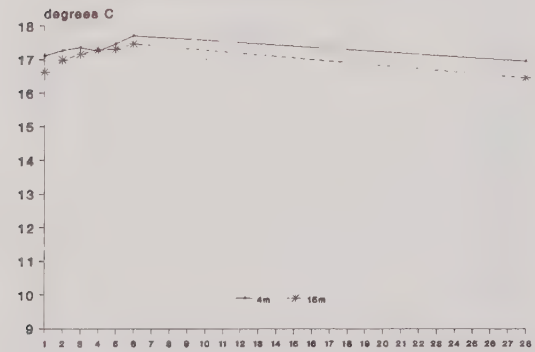
B. % surface light at 9m

C. Total daily irradiance

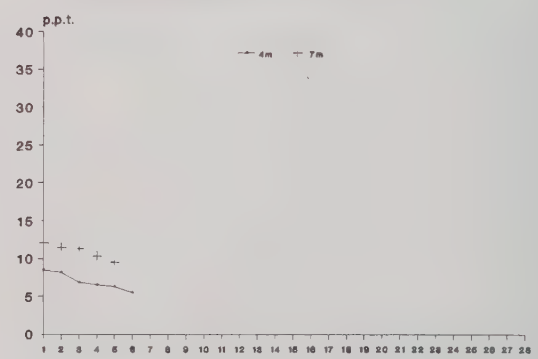


D. % total light at 9m

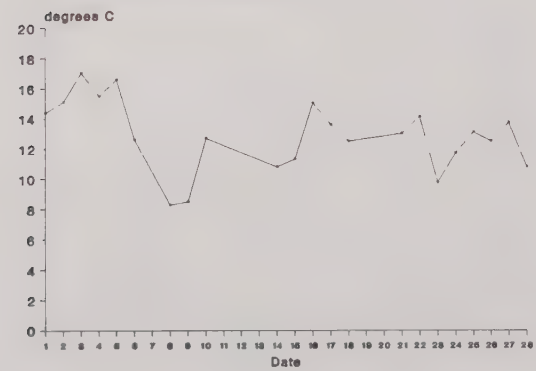
E. Mean daily water temperature



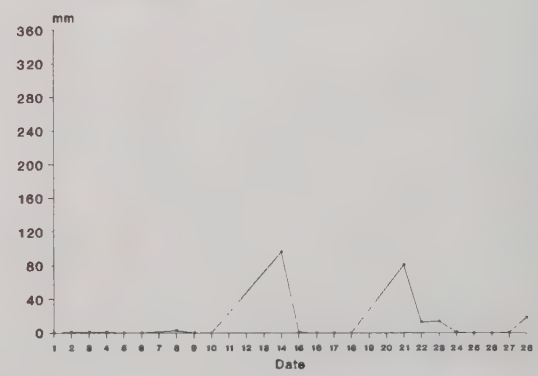
F. Mean daily salinity



G. Mean daily air temperature

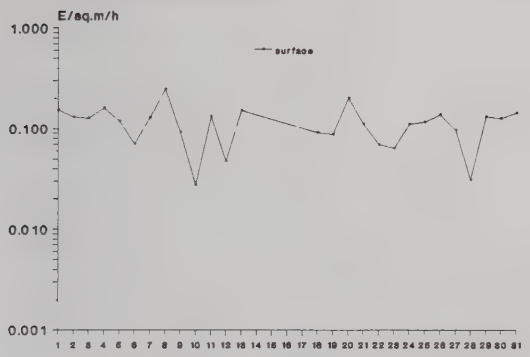


H. Daily rainfall

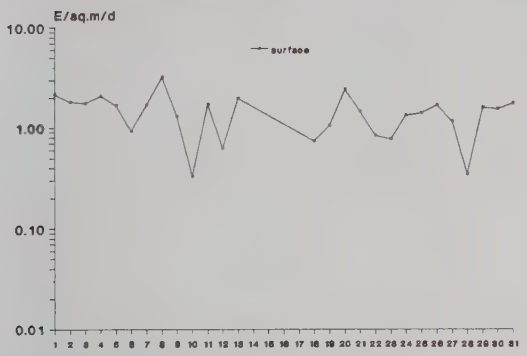


March 1989

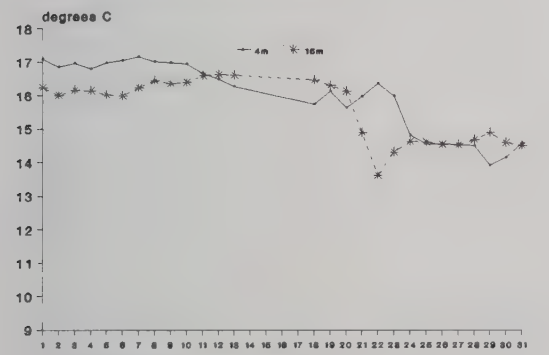
A. Mean daily irradiance



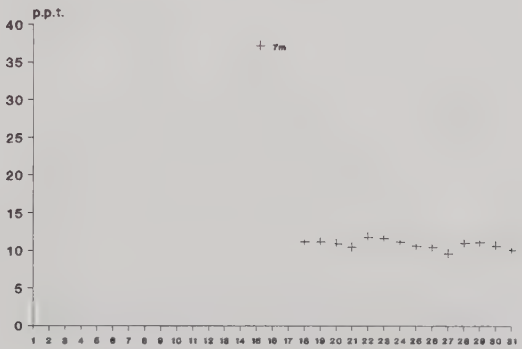
C. Total daily irradiance



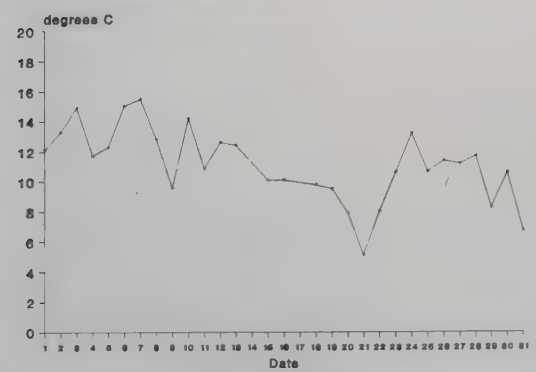
E. Mean daily water temperature



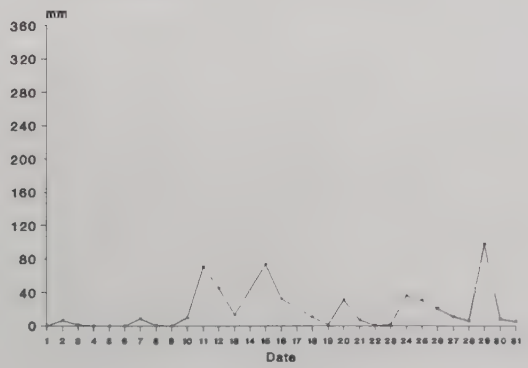
F. Mean daily salinity



G. Mean daily air temperature

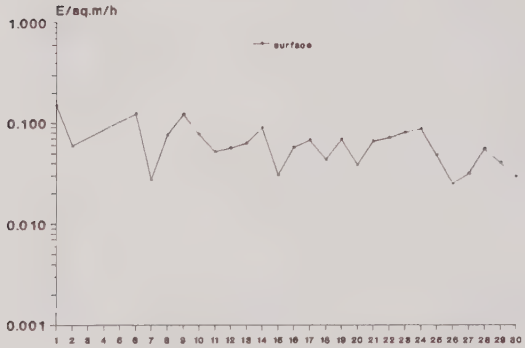


H. Daily rainfall



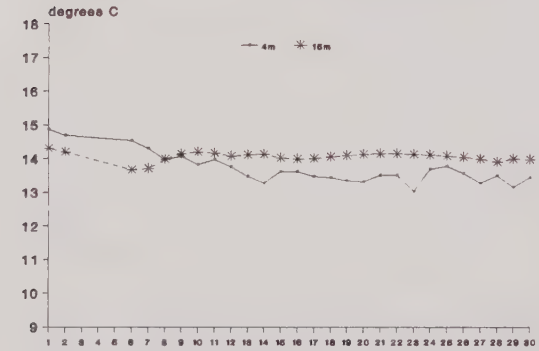
April 1989

A. Mean daily irradiance



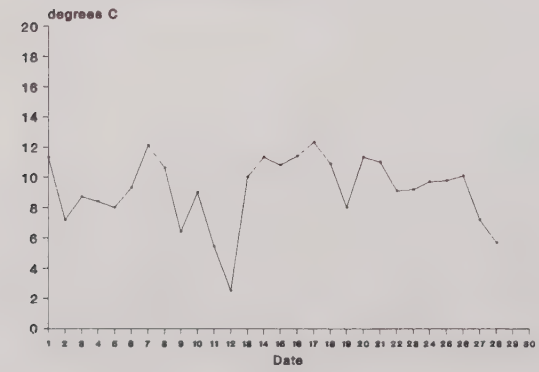
C. Total daily irradiance

E. Mean daily water temperature

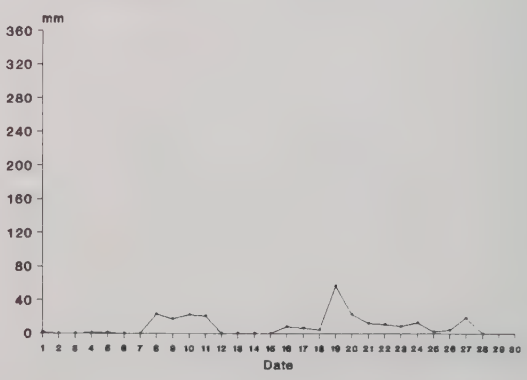


F. Mean daily salinity

G. Mean daily air temperature

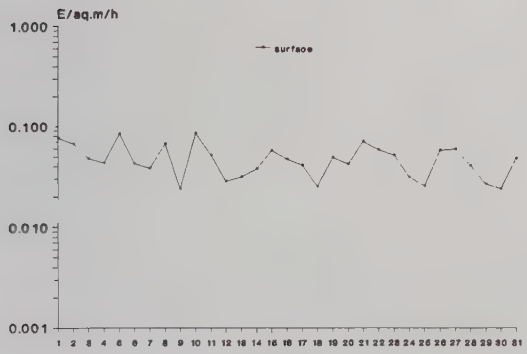


H. Daily rainfall

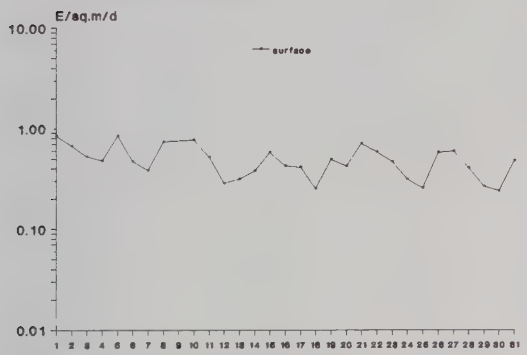


May 1989

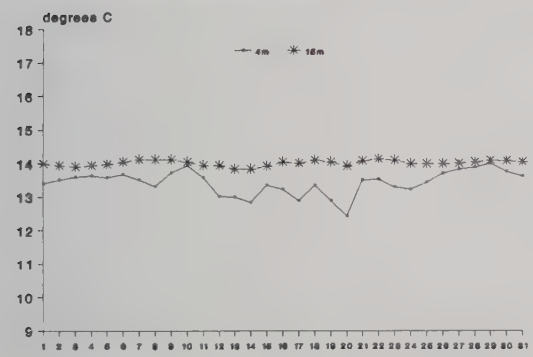
A. Mean daily irradiance



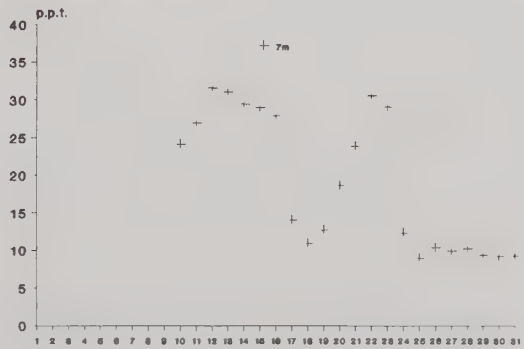
C. Total daily irradiance



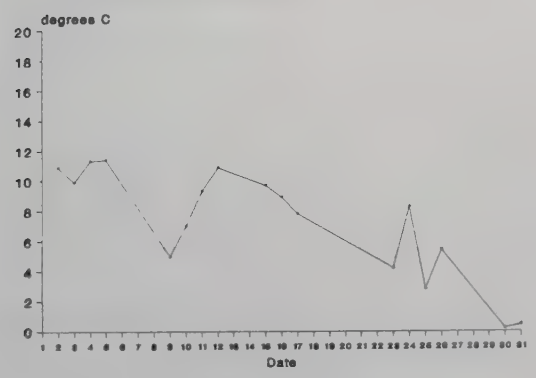
E. Mean daily water temperature



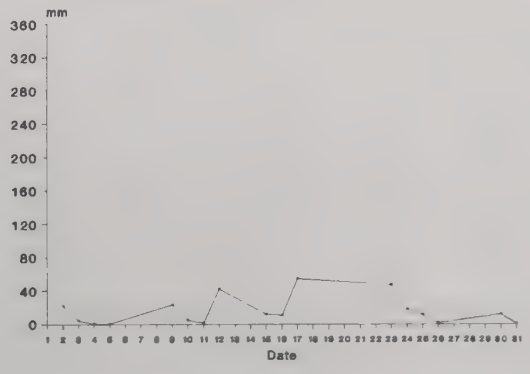
F. Mean daily salinity



G. Mean daily air temperature

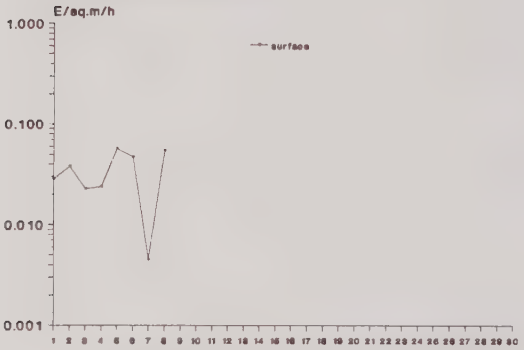


H. Daily rainfall

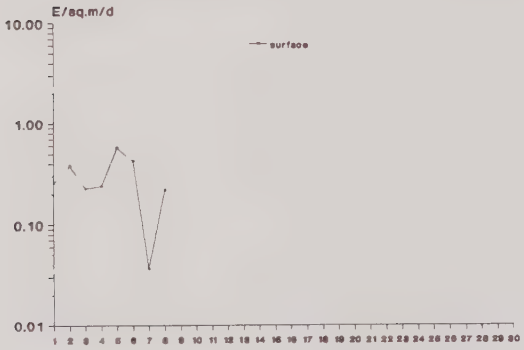


June 1989

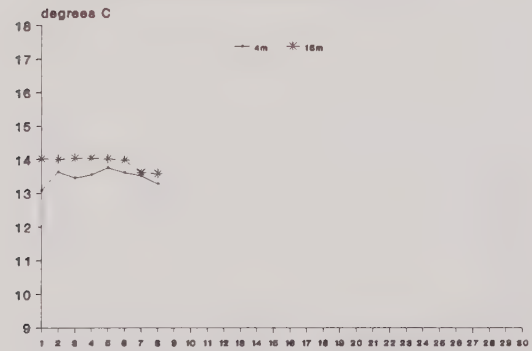
A. Mean daily irradiance



C. Total daily irradiance

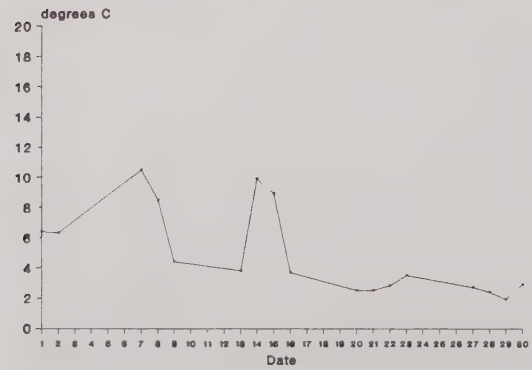


E. Mean daily water temperature

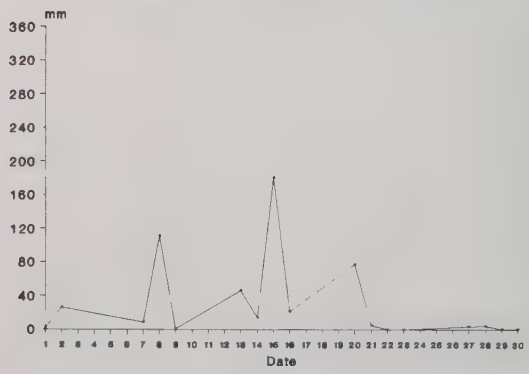


F. Mean daily salinity

G. Mean daily air temperature

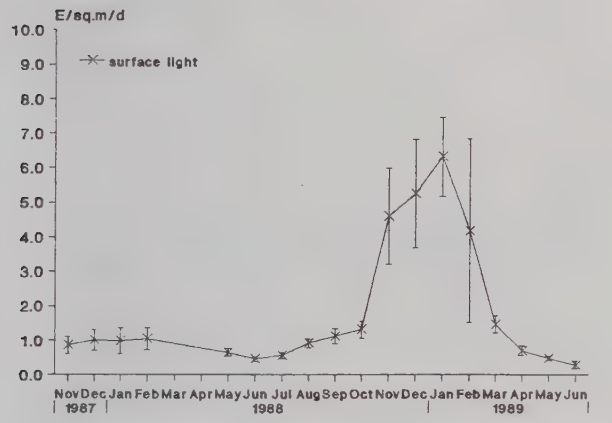


H. Daily rainfall

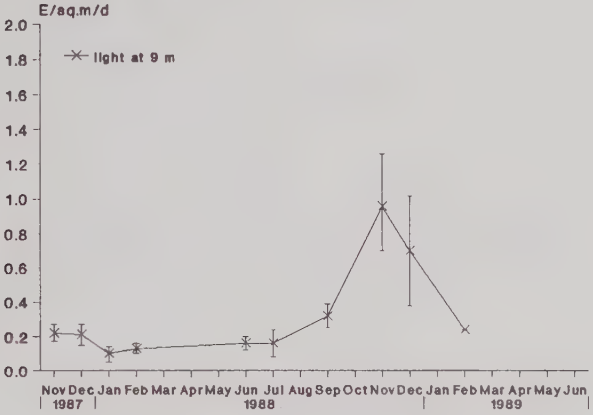


APPENDIX 2. Monthly means for all parameters from November 1987 to June 1989.

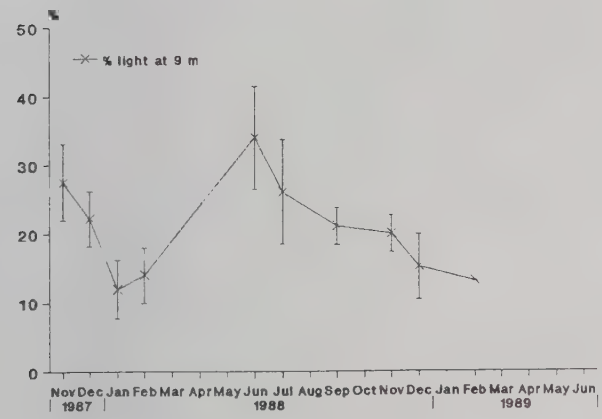
A. Mean daily irradiance per month



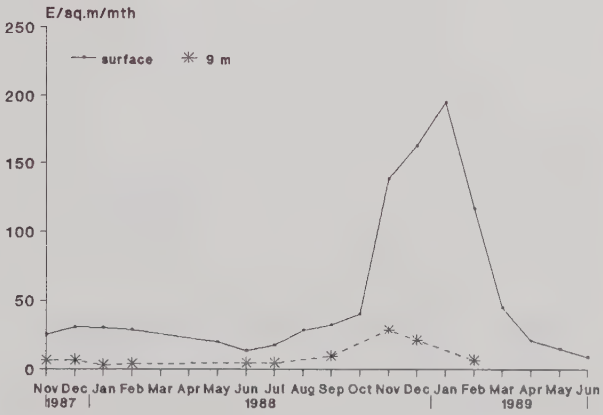
B. Mean daily irradiance per month



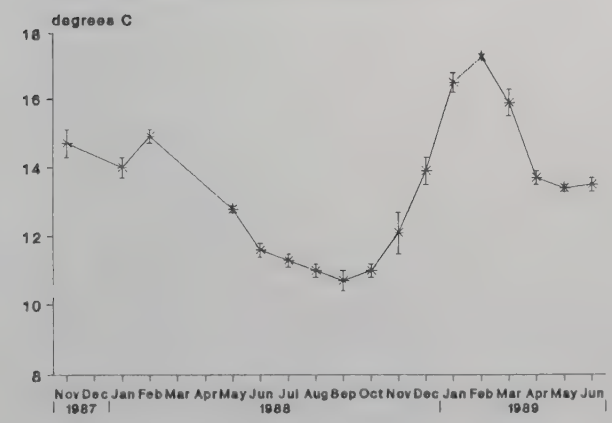
C. Mean daily irradiance per month



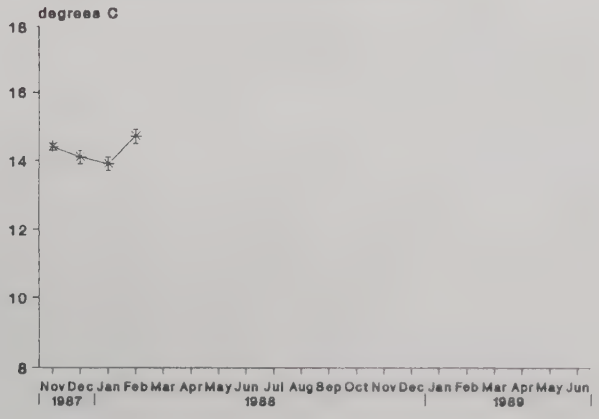
D. Total monthly irradiance



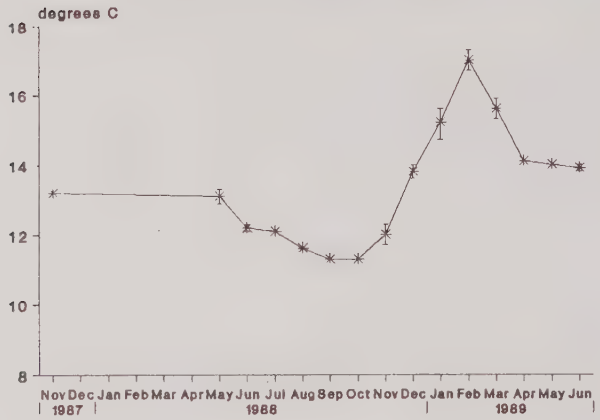
E. Mean monthly water temperature at 4 m



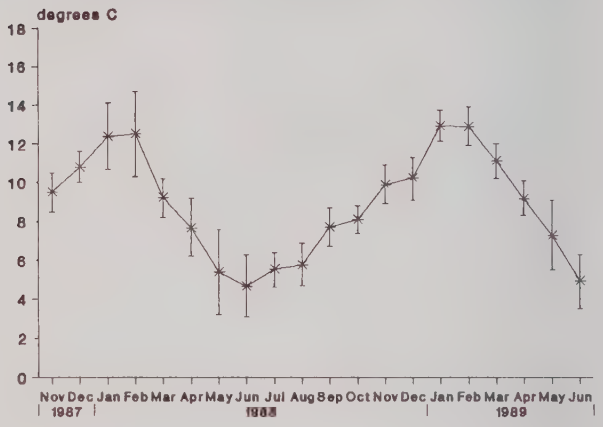
F. Mean monthly water temperature at 7 m



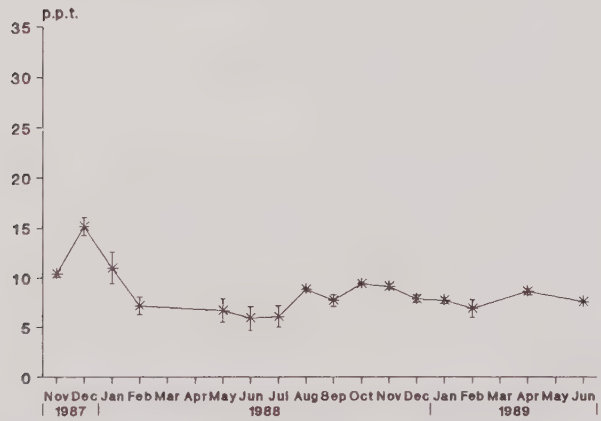
G. Mean monthly water temperature at 15m



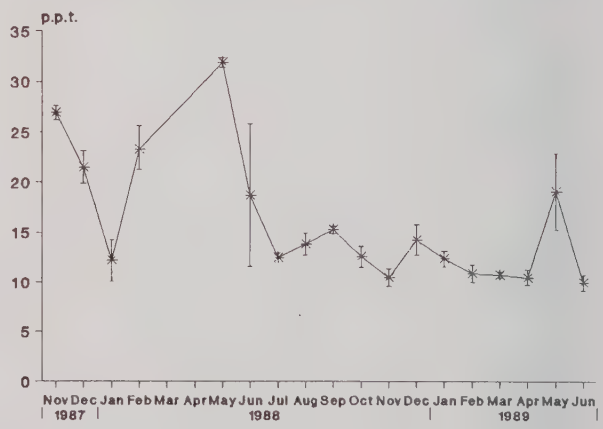
H. Mean monthly air temperature



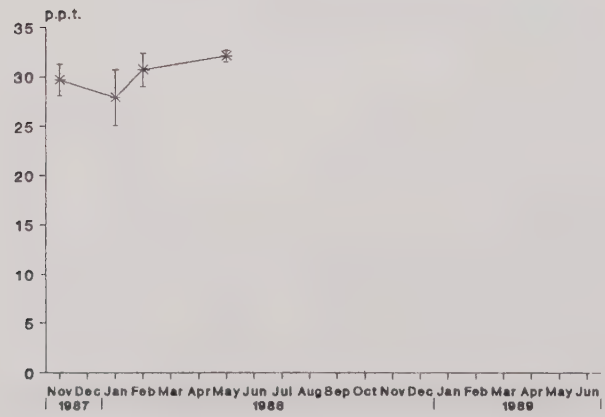
I. Mean monthly salinity at 4 m



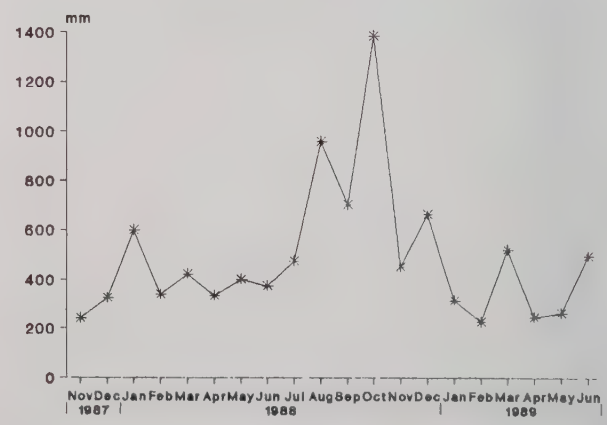
J. Mean monthly salinity at 7 m



K. Mean monthly salinity at 15 m

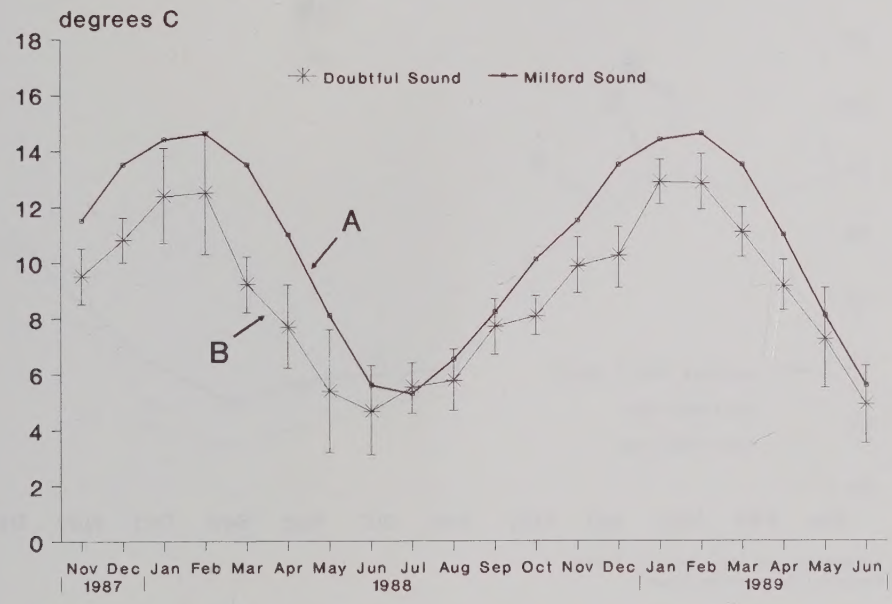


L. Total monthly rainfall, Deep Cove



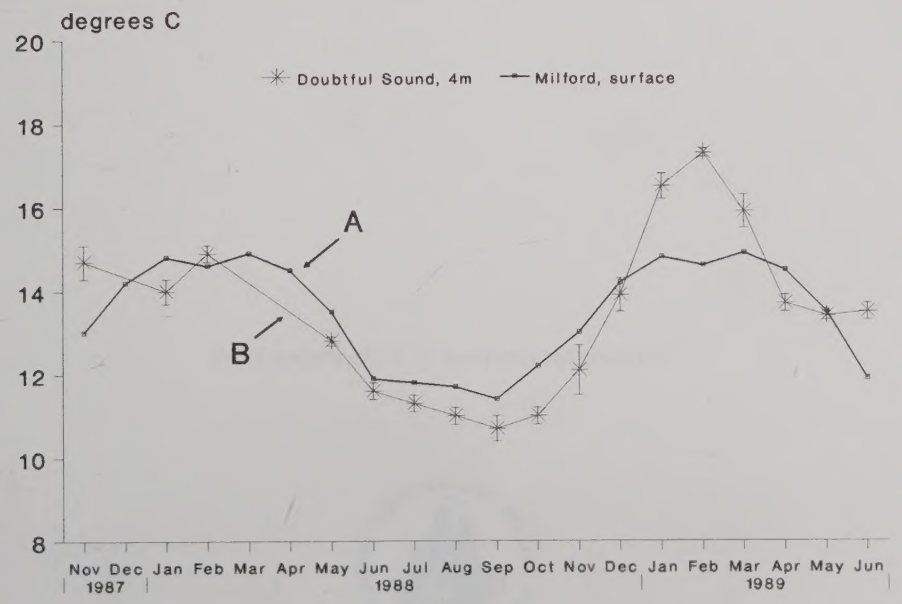
APPENDIX 3. Graphic summaries of long-term physical data.

A. Mean monthly air temperature



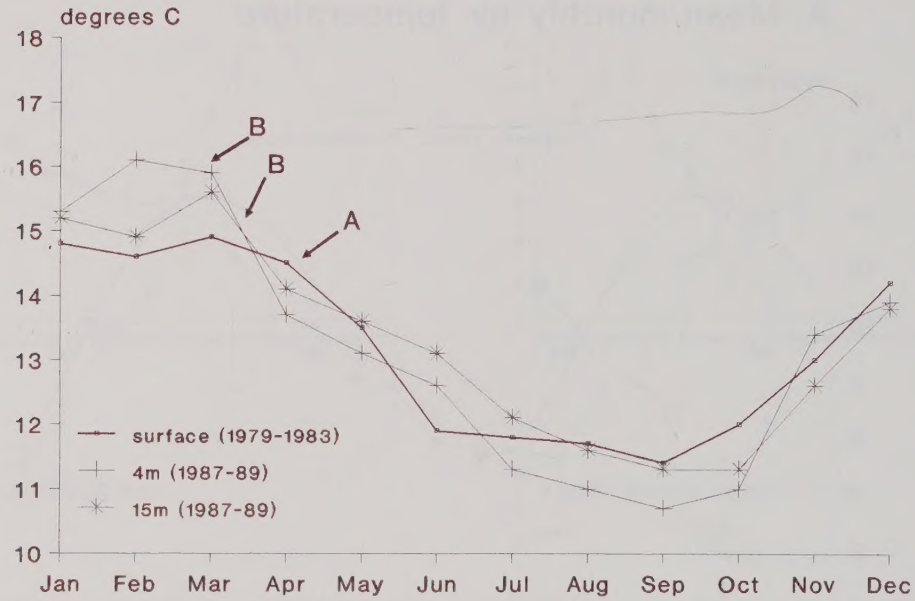
A. long-term mean, after Stanton (1986)
B. this study

B. Mean monthly water temperature



A. long-term mean, after Stanton (1986)
B. this study

C. Mean monthly water temperatures



A. Milford Sound, after Stanton (1986)
B. Doubtful Sound, this study

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